www.RUVIVAL.de

TUHH
Hamburg University of Technology

aww
Institute of Wastewater Management and Water Protection

hoou.de

RUVIVAL
Publication Series

03

01/2018

RUVIVAL Publication Series Volume 3

Founders & Editors in Chief
Ruth Schaldach
Prof. Dr.–Ing. Ralf Otterpohl

Co-Editors
Isidora Vrbavac
Tina Carmesin

Layout & Design
Isidora Vrbavac

Authors
Dr.-Ing. Joachim Behrendt
Dario Fröndhoff
Andrea Munoz Ardila
Maria Monina Orlina
Máryeluz Rueda
Ruth Schaldach

Address
Institute of Wastewater Management
and Water Protection
Eißendorfer Straße 42
21073 Hamburg

January 2018

Identification
http://nbn-resolving.de/urn:nbn:de:gbv:830-88218207
ISSN 2567-8531

www.RUVIVAL.de

Stay in touch

Website: www.ruvival.de

E-mail: ruvival@tuhh.de

Facebook: @ruvival

Twitter: @ruvival_project

YouTube & Vimeo: RUVIVAL

Picture credits can be found at the end of each paper.

Please cite as indicated in each paper.

Please consider the environment before printing.

From the Editors

Preface by Ruth Schaldach

This is the third volume of RUVIVAL Publication Series. This open access publication series is developed within the e-learning project RUVIVAL, which you can always visit under ww.ruvival.de.

Our Project is a pilot project of an initiative by the City of Hamburg to establish with all public universities in Hamburg the Hamburg Open Online University (www.hoou.de). The idea is to make the knowledge of universities not only available online for the broader public, but also to invite people to participate in the knowledge production and exchange.

RUVIVAL is dedicated to sharing knowledge necessary to face rising environmental challenges, especially in rural areas and empowering people to restore and rebuild them. RUVIVAL collects practices and research conducted from the Institute of Wastewater Management and Water Protection (AWW) at Hamburg University of Technology (TUHH), but also from all over the world. Each contribution in this publication is connected to further interactive multimedia material, which can be found, read, tested, watched, shared and extended on the RUVIVAL-website.

Each volume of RUVIVAL Publication Series takes on a topic, which represents a cornerstone of sustainable rural development. The approach draws a systematic and interdisciplinary connection between water, soil, nutrition, climate and energy. Measures which enable sustainable use of land resources and improvement of living conditions are reviewed and new ideas developed with consideration of their different social, political and demographic contexts.

In case of Volume 3, we are talking about the synergies between ecological sanitation and sustainable land management. As the previous two volumes, Volume 3 consists of a collection of three literature reviews written in collaboration with Master students, PhD students and researchers at the AWW at Hamburg University of Technology. The work is supervised by at least one senior researcher at the AWW Institute, who is specialised in a related subject. The entire process entails several feedback rounds and a final presentation of the work, where other researchers of the Institute submit their additional comments. This outcome is then published on the RUVIVAL Webpage as a working paper and the broader audience is asked to participate with further feedback or ideas. The final version of the literature review is only included in the publication series once all feedback has been incorporated and the paper was once again reviewed by the supervising researchers.

Beyond providing open access to research to a broader public and making it available for practitioners, we strive to directly include our readers in developing the materials. In this way, we hope to connect to the knowledge of a broad public and provide a deeper understanding of research fields important for sustainable rural development and in areas in need of landscape restoration.

Introduction by Ralf Otterpohl

All topics of volume 1 through 3 are related on several levels. All are part of restoration engineering, a subject that is still not very common. The main goal of my team and me is to encourage all stakeholders to know and to combine those wonderful methods in implementation. Single Elements that are usually implemented can be efficient by themselves but have proven to perform miracles if applied in combination. However, the challenge is to choose and apply all elements in a professional way, to adapt them to the given situation and to consider the systems many interactions, too. Methods may look simple on the first view, but especially simple and low-cost methods require experience. Few professional failures can be worse than working with villagers, who often put a lot of their hope, money and labour into implementation, and then running them into famine with ill designed systems. Restoration engineering has the potential to raise productivity of eroded areas hundredfold. Income, excellent nutrition and well-being for family farmers and their children, in my point of view, should be the foundation for self-promoting solutions.

Urine Utilisation

If you wonder why urine can be a serious topic for rural development, you should look at its properties. A major part of macro- and micronutrients (trace elements) contained in urine will be concentrated – if dilution caused by flushing can be avoided or at least greatly reduced. For many years there was euphoria in ecological sanitation, we thought that almost full nutrient recovery is possible with an economically feasible effort. However, after a lot of research and many pilot projects later it turned out that urine-diversion toilets are far trickier than previously thought. For collection of the larger part of urine, the front basin should cover around half of the bowl, but this is already too big for a clear diversion. The big upside of urine collection is that urinals have matured and no-flush is absolutely possible. My personal conclusion is that urine diversion is great for very rural settings, where the required 400 m² per person for utilisation is available on or near site. For peri-urban and urban situations, I personally think that collecting all excreta in Terra Preta Sanitation container toilets makes a lot more sense. Transporting urine or all excreta is no big difference and both fractions should be treated before utilisation.

Many experts within the field of ecological sanitation promote the utilisation of urine for direct application to vegetables. On the one hand, this will bring mineral fertiliser into the system. As a result this is no longer organic gardening. On the other hand, there are pharmaceutical residues and hormones in urine that I prefer not to have in food. Consequently, the tomato becomes a remedy of urine therapy, but is only suitable for the person who donated the urine. I promote the utilisation for industrial crops and reforestation. Most people around the world refuse to eat urine fertilised meals: an assessment with a participatory approach will make this obvious and exclude this option for food crops (crop restrictions). A good compromise is to compost urine with woody waste materials and maybe some charcoal, to convert it to organic fertiliser. This will not eliminate all pharmaceuticals, but they will be washed out over time. These are my personal thoughts that differ much from most people of our ecological sanitation community.

Terra Preta Sanitation

Utilising Terra Preta means learning from the wisdom of ancient civilisations in the Amazon region. It becomes more and more obvious that ancient civilisations were partly far more advanced and date far further back than we can imagine (see the bestsellers and presentations by Graham Hancock). The big breakthrough in ecological sanitation was the urine-diverting dry toilet (UDDT), as first developed in modern times by sanitation specialists from Sweden, as it presents a solution for the major disadvantage of toilets with large composting chambers loosing most of the nutrients in leakage. In my personal experience from around the world, I have to say that UDDT can be quite good when very well managed. However, even the best projects are not excellent and are rarely self-promoting on a large scale. The first toilets that introduced lactic acid fermentation and charcoal addition were set up by the Terra Preta pioneers Dr. Jürgen Reckin and Dr. Haiko Pieplow. While there is clear historic evidence for the addition of ground charcoal, the addition of lactic acid bacteria and a sugar source is a plausible hypothesis of Haiko Pieplow. Haiko's idea gave rise to what we call Terra Preta Sanitation.

I will always remember Chris, then a member of my ecosan-research team coming down the stairwell at TUHH. At that time, he had done years of experiments with different types of UDDTs, specifically with our idea to include vermi-composing into the toilet vaults. Now, this was the first time I had seen him after the first set of experiments with container toilets under lactic-acid-fermentation. He said something like 'Prof, I never imagined that toilets can be that simple!' Dr.-Ing. Chris Buzie had managed a large sanitation research group for TUHH in West Africa and therefore his words had weight. This was confirmed over the following years of intensive practical as well as theoretical research.

UDDT is a suitable solution for very rural areas and isolated compounds. People have use for the products and typically operate the units by themselves. I consider UDDTs a very difficult system for more densely populated peri-urban and urban areas. Many larger projects for multi-story houses, one of them designed by me, failed. However, if professional container toilets under lactic acid fermentation are built into such apartment blocks, they can be emptied by gravity to an intermediate tank. In my view, based on extensive experience, this type of Terra Preta Sanitation according to TUHH can serve most situations in more densely populated areas of the world. Spray instead of 'dry' cleansing helps the easy utilisation without causing much dilution. The key to success is obviously a proper explanation to prospective users and a professional local collection service with suction trucks.

Charcoal can be added for composting – or, more realistically – for the direct on-site humus building application of the substrates to soil. The latter method will be far less complicated and has only one transporting step to the land and fill the distribution barrels. More woody waste material shall be added to compensate for the excess of the mineral fraction of the material. The sanitation problem is solved, however so far only on the technical and logistical level as well as in terms of economic feasibility. A major advantage is that such toilets can be installed in upscale metropolitan areas and poor peri-urban communities.

Sustainable Irrigation

The most sustainable, simplest and cost efficient irrigation by far is natural rainfall in a healthy environment. Rainfall is tinkered in many respects: soil degradation, geoengineering without public consent, radioactivity and more.

Technical irrigation should be avoided by clever choice of plants, rising of humus contents, reforestation. All of this links again to many RuVival topics. Rainfall can stabilise, if reforestation and improved humus layers with year round vegetation cover is ensured on a larger area. Only if really needed, technical irrigation should be implemented.

There is a wide choice of systems. In water scarce areas – irrigation is often the cause and deepens the problem. In the first place, irrigation systems should be embedded in clever rainwater harvesting structures. It is commonly taught that drip-irrigation is the most efficient. However, subsurface irrigation can be far better, as evaporation is further reduced, if a good system is installed in a proper way. Unfortunately, there are many products on the market that do not work well. Proven systems should be applied. On the other hand, when put into pure sand, the water may just go down instead of reaching the roots – this is a specific issue for the seeding or seedling phase. Water needs to reach the seeds. They should be part of a humus rich system to be efficient. There is plenty of information available otherwise, so please find out what best suits which purpose.

Inside This Volume

Literature Review on the Utilisation of Urine as a Fertiliser in Agriculture

Andrea Munoz Ardila, Máryeluz Rueda, Ruth Schaldach, Joachim Behrendt

Sustainable Development Goal (SDG) 6, 'the water and sanitation Goal, is in need of a major push. The time is right, thus I encourage you all to join together to develop concerted global action to deliver on the targets of [that Goal].'

Peter Thomson, United Nations General Assembly President (UN 2017)

Please cite as: Munoz Ardila, A, Rueda, M, Schaldach, R & Behrendt, J 2018, 'Literature Review on the Utilisation of Urine as a Fertiliser in Agriculture' in R Schaldach & R Otterpohl (eds), RUVIVAL Publication Series, vol. 3, Hamburg, pp. 8– 18, <http://nbn-resolving.de/urn:nbn:de:gbv:830-88218207>.

Abstract

Urine contains four important nutrients for plant growth: nitrogen (N), phosphorus (P), potassium (K) and sulphur (S) and its use as fertiliser can not only recover these nutrients, but also reduce the use of chemical fertilisers and freshwater, as well as minimise the wastewater and excreta contamination of surface and open waters. However, if not managed properly, the risk of pathogen transmission, soil salinisation and pharmaceutical contamination, as well as strong and offensive odour, can cause significant health problems and discomfort. Other challenges that have to be addressed in the process of urine utilisation in agriculture are separation techniques, storage time, urine amount to be applied, odour prevention and transport. The possibilities and difficulties of this technique are addressed in this paper. The utilisation of urine in agriculture can help to achieve the Sustainable Development Goal (SDG) 6: 'ensure availability and sustainable management of water and sanitation for all' of the 2030 Agenda.

Keywords: *urine fertilisation, ecological sanitation, nutrient recovery, struvite precipitation, literature review*

Introduction

Degradation of fresh water, improper sanitation systems and disposal of wastewater increase water stress. Sanitation systems have a big impact on the environment in regard to discharges to water bodies, air emissions, soil degradation, as well as use and reuse of natural resources. Therefore, new approaches in sanitation and irrigation should be pursued, aiming towards public health, water savings and water pollution prevention. The use of urine in agriculture can help to achieve these aims and recycle the nutrients from human excreta. However, if not used properly, many complications can arise, such as pathogen and pharmaceutical contamination, as well as social acceptance, among others (WHO 2006).

Urine contains four important nutrients for plant growth: nitrogen (N), phosphorus (P), potassium (K) and sulphur (S). Phosphorus, for example, is a limited resource and is mainly used as a fertiliser for plant productivity. Nevertheless, if it reaches surface waters in high amounts, it can cause eutrophication of the water bodies. Moreover, phosphorus elimination, as well as recovery, requires advanced wastewater treatment processes. Hence, direct recycling from human urine could support both crop production and the reduction of treatment steps needed, if flush toilets are used, to remove it from wastewater (WHO 2006).

In addition, the use of urine minimises different negative impacts on the environment, such as the amount of wastewater reaching surface water and groundwater, as well as the amount of freshwater use in case of flush toilets. Urine utilisation also reduces the use of chemical fertilisers, which can have a negative impact on the environment and human health. This in turn reduces the expenditures on waste management and chemical fertilisers (Haq & Cambridge 2012; WHO 2006). However, according to the guidelines by the World Health Organisation (WHO) (2006), there are different steps that have to be followed to guarantee user health protection. Other challenges that have to be addressed within urine utilisation in agriculture are separation techniques, storage time, amount of urine to be applied, odour prevention and transport.

In 2010, United Nations (UN) declared access to clean water and sanitation an essential human right. Prior to this, already in 2000, the 7th of the 8 Millennium Development Goals (MDGs) was set to 'ensure environmental sustainability' and one of the sub-targets was 'to halve, by 2015, the proportion of people who are unable to reach or afford safe drinking water, and without access to basic sanitation' (UN 2010, p. 2). This goal was partially met in 2015. The proportion of people with access to safe drinking water has increased between 1990 and 2015 from 76 % to 91 %. This means that 2.6 billion people gained access to improved water sources. However, the access to basic sanitation is, with an improvement between 1990 and 2015 of 14 % (from 54 % to 68 %), still below the MDG target. Although 2.1 billion people have already gained access to basic sanitation, 2.4 billion people still live without an improved sanitation system and 946 million people still practice open defecation (UN 2015). The 2030 Agenda for Sustainable Development, an expansion of the MDGs, contains 17 Sustainable Development Goals

(SDGs) with SDG 6 aiming to ensure 'availability and sustainable management of water and sanitation for all' (UN-Water 2016, p. 8). Regarding sanitation in specific, the goal is to achieve 'equitable sanitation and hygiene for all and end open defecation' by 2030 (UN-Water 2016, p. 9).

This paper will review the available research on urine utilisation for agricultural purposes, its benefits and risks, as well as treatment and application methods. The focus will be on small-scale use, meaning small households and private use, aiming to acknowledge the benefits of urine nutrient recovery and support basic ecological sanitation systems.

Urine as a Valuable Resource

Since nutrients in urine essentially originate from arable land and its crops, closing the nutrient loop and giving them back to arable land is a rather logical process. Urine contains the majority of nutrients excreted by the body and has been studied for crop fertilisation in many countries, such as Germany (Clemens et al. 2008), Sweden (Andersson 2014), India (Andersson 2014), Ethiopia (Kassa, Meinzinger & Zewdie 2010) and the Philippines (Soria Akut 2014), among others. The utilisation of urine as a crop nutrient source has recently been receiving greater attention among researchers. Unfortunately, it is still highly underestimated in the present agricultural and horticultural practices (Karak & Bhattacharyya 2011).

Nutrients in Urine and Its Potential as Fertiliser

Plants have different growth limiting factors, such as light, water, soil structure and nutrients. Nutrients can generally be divided into macro and micronutrients. Macronutrients are taken up in higher amounts compared to micronutrients. These are nitrogen (N), phosphorus (P), potassium (K), sulphur (S), calcium (Ca) and magnesium (Mg). The most important one is nitrogen, which is taken up as nitrate (NO_3^-) or ammonium (NH_4^+) ions. In urine, nitrogen is available between 75 – 90 % as urea and ammonium. The enzyme urease converts urea to ammonium, which is directly available for the plants. Phosphorus is taken up by plants as orthophosphate ions (HPO_4^{2-}, $H_2PO_4^-$), which are available in urine and can be directly taken up. The presence of potassium and sulphur in urine is in form of ions, which are also directly plant available. Thus, the nutrients provided by urine can be directly taken up for plant growth and have a similar composition to chemical fertilisers (Jönsson et al. 2004; Uchida 2000).

A fully grown human body excretes nutrients almost in the same amount as consumed. Because of this, the amount of nutrients in urine (N, P, K and S) can be calculated from the nutrient intake. On average, one person produces between 0.8 and 1.5 L of urine per day, which equals around 550 L of urine per person and year (WHO 2006, pp. 9–10). Nutrient concentration, as well as the amount of urine produced, depends on many factors, such as diet, climate, gender, water intake, physical activity and body size. For example, the proportion of the total nitrogen, phosphorus and potassium in urine, as opposed to the concentration in faeces, are for an average person in Sweden nearly 88 %, 67 % and 73 % respectively. Countries like Haiti, India and Uganda have much lower nutrient concentrations (nearly half of those of Sweden) (Eawag, Gensch & Spuhler n.d.; Jönsson et al. 2004).

Health Aspects

Urine produced by the human body is mostly sterile and has a high hygienic quality compared to faeces. The risk of urine contamination is mainly a result of cross contamination with the pathogens contained in faeces. For the most part, this can be overcome through the use of urine diverting systems. However, another source of pathogens can be an infection on the urinary passage (Clemens et al. 2008; WHO 2006).

Studies done by researchers at Hamburg University of Technology (TUHH) have revealed the risks associated with pharmaceutical residues, in particular water-soluble substances, which are excreted via urine (Gajurel et al. n.d.; Tettenborn, Behrendt & Otterpohl 2008; Winker 2009). Many of those do not exhibit good biodegradability and can accumulate in plants, entering the human food chain. Additionally, it is important to consider that pharmaceuticals present in urine, derived from small collectives with several persons under medication, can be transferred to groundwater when urine is used as a fertiliser (Behrendt et al. 2009; Gajurel et al. n.d.). However, Winker et al. (2010) argue, that concentrations of pharmaceutical residues in urine do not accumulate to levels affecting plant growth as the load of hormones and antibiotics in human urine is much lower compared to the load in animal manure, which is already used for agricultural purposes. Other potentially harmful substances contained in urine are heavy metals. However, the concentrations are also lower compared to chemical fertilisers and farmyard manure (Clemens et al. 2008).

Although the risks for human health and environmental contamination are low, efficient pathogen removal is necessary before applying urine as a fertiliser (Tettenborn 2012).

Conditioning of Urine for Agricultural Purposes

The management of urine begins with the separation of human excreta, or rather the separation of urine from faeces. Afterwards, urine can be treated depending on the location of the collection site and the application target. Home collection for private use should undergo different treatment than public collection for broader, public use. To follow guidelines for the application rate of urine as a fertiliser is recommended (Tettenborn 2012).

Urine Separation

Alternatives to the conventional centralised water driven wastewater systems have been developed and applied for a range of purposes, such as the control of the wastewater load at wastewater treatment plants, the reduction of micropollutants and contamination of surface and groundwater, the reduction of freshwater use and the reuse of nutrients contained in excreta directly at the source (Behrendt et al. 2009; Tettenborn 2012).

Focusing on the so called dry sanitation systems, which do not use water, different urine diverting dry toilets (UDDT) have been developed with the main purpose of separating human urine from faeces at the source and thus enabling a better recycling of nutrients from human urine and the composting of human faeces. An UDDT has two outlets and two collection systems; one for urine and one for faeces. Nevertheless, UDDTs have some adaption challenges, due to their low acceptance and the fact that improper use can lead to clogging (Eawag, Wafler & Spuhler n.d.) and cross contamination. Urine is stored for an appropriate period in order to allow for hygienic treatment and is finally used as a crop fertiliser (Rieck, Münch & Hoffmann 2012).

Another possibility to collect urine is via urinals, and although they are most common for men, some models have also been developed for women. Urinals for men can be either vertical wall-mounted units, or squat slabs. Urinals for women have raised footsteps and a sloped channel or catchment area to direct the urine towards the collection system (Tilley et al. 2014). Other alternatives for women are intravaginal urinals designed to be worn for long time periods and portable women's urinal devices for use in an upright position (Möllring 2003). Moreover, the technology used for urine separation depends on the physical context and needs to be adapted to user demands.

Treatment for Use in Agriculture

There are different options to eliminate pathogens. The designated urine use and collection source determine the prior treatment requirements. Two of the possible treatment options will be explained further in this paper: urine storage and struvite precipitation. Urine storage as hygienic treatment is mostly sufficient on a small-scale (household level), if the recommendations given in the WHO guidelines are followed (Clemens et al. 2008; Eawag, Gensch & Spuhler n.d.; Udert et al. 2015; WHO 2006). Moreover, some scientists see the agricultural use of urine primarily as a favourable option for rural areas (Behrendt et al. 2002; Soria Akut 2014). In urban areas, where the population density is high, the storage and transport of separately collected urine can be difficult. Thus, it is necessary to employ concentration techniques, that permit not only treatment, but also volume reduction (Behrendt et al. 2002).

Hygienisation and Urine Storage

Storing urine increases the pH value and the ammonia content, improving the die-off rate of pathogens and preventing the breeding of mosquitos. According to WHO guidelines, the optimal storage period is 1 month, when a family's urine is used to fertilise individual plots for their consumption (WHO 2006). However, when urine is collected from many households or facilities and subsequently mixed, high pH, temperature and concentration, as well as long storage periods are recommended, in order to eliminate pathogens and viable viruses. The optimal storage period is 6 months at 20°C or higher (Karak & Bhattacharyya 2011; Richert et al. 2007; WHO 2006).

At excretion, the pH of urine is normally around 6.0 but can vary between 4.5 and 8.2. In the collection vessel, the pH of urine increases to 9.0 – 9.3 and has a high ammonium concentration. This leads to a risk of losing nitrogen in form of ammonia if the vessel is ventilated. Thus, the vessel should not have any ventilation but be pressure equalised, which also helps to eliminate malodours (Jönsson et al. 2004). It needs to be considered that hormones and pharmaceuticals cannot be removed through urine storage.

An advantage of this technique is its simplicity and low-cost implementation and maintenance. It can be implemented almost everywhere, where place for storage tanks can be designated (Miso & Spuhler n.d.).

Concentration and Recovery Techniques

A simple and fast concentration technique is struvite precipitation, which is mostly used for the recovery of phosphorus. Struvite precipitation happens naturally, when magnesium ions react with phosphate and ammonium ions contained in urine. They precipitate and form mainly struvite ($MgNH_4PO_4{\cdot}6H_2O$) and apatite ($Ca_{10}(PO_4)_6(OH)_2$) crystals. These are found in form of sludge at the bottom of the collection vessel and can be used directly with the urine, or separated and then filtered and dried to create an odourless powder. However, the chemical reaction happens only as long as there are soluble magnesium ions in urine and the amount of magnesium in urine is low. For an overall use of the phosphate ions, the reaction can be stimulated by adding magnesium to the stored urine (Jönsson et al. 2004; Miso & Spuhler n.d.; Udert et al. 2015).

Struvite can be used for crops with a high phosphorus demand and offers a slow nutrient release. Nevertheless, the available nitrogen amount is not sufficient for optimal plant growth. Thus, if only struvite is used as fertiliser, it is recommended to use a combination of other fertilisers in addition. Furthermore, struvite can have a negative impact on soil (high pH) and nutrient uptake of plants, when the application rate is overdosed (Miso & Spuhler n.d.). After struvite precipitation the remaining nitrogen in urine can be recovered by air stripping followed by absorption in sulfuric acid (Antonini et al. 2011; Behrendt et al. 2002).

Other, much more extensive methods also exist, such as nitrification together with distillation and electrolysis. Although a combination of nitrification and distillation recovers all nutrients through the nitrification process and concentrates the solution through distillation, it is more complex than struvite precipitation. The electrolysis process could be used in very small on-site reactors and then integrated into toilets, due to high degradation rates and simple operation. However, the electrolysis process degrades ammonia, so there is no major recovery of nutrients. The system should be used when there is no need for nutrient recovery, but a high need for on-site treatment, for example, in urban areas with a special need for hygienic treatment of excreta (Udert et al. 2015).

Proper Urine Application Rates

The application rate of urine depends not only on its nutrient content, but also on the main goal of urine utilisation. Urine is, for the most part, an N-fertiliser, due to the high content and quality of nitrogen. Nutrient concentrations in urine and in soil, as well as the needed nutrient concentration for specific crop growth must be taken into consideration. It has been estimated that the urine production of one person (550 L/year) is sufficient to fertilise 300 – 400 m^2 of arable land per year with a nitrogen level of about 3 – 7 g N/L urine. This means 1.5 L of urine should be applied to one square metre of land, corresponding to an application rate of 40 – 110 kg N/ha (Jönsson et al. 2004).

If the main goal is to replenish phosphorus, the urine application rate should be about 6 kg P/ha, which corresponds to 0.9 L of urine per square metre and a phosphorus level of 0.7 g P/L urine. At this rate, a fertilisation area of 600 m^2 can be achieved for phosphorus fertilisation based on a single person's yearly urine production (Jönsson et al. 2004).

Urine can be applied to crops without dilution, or it can be diluted, with the water to urine ratio from 1:1 to 10:1. Through dilution, the total volume of urine to be spread increases, which may increase the need for equipment and labour. However, it is important to remember that urine is to be used as fertiliser and not as an irrigation method. Urine and water can be applied together, keeping in mind both the nutrient and water requirements of the crops. Fertilisation with urine should be concluded before the final third or quarter of time before harvesting, to assure good hygiene of the crops, especially if consumed raw (Jönsson et al. 2004; Karak & Bhattacharyya 2011; Tilley et al. 2014; WHO 2006; eds Winblad & Simpson-Hébert 2004).

Furthermore, urine has a better effect on soils with a high content of humus, due to the beneficial soil bacteria supporting the conversion of urine nitrogen into plant available nitrogen. If the soil is poor in humus, according to Windblad & Simpson-Hébert (2004), the best way to maximise the urine potential is to combine it with the humus formed through processed faeces. However, the usage of humus produced from faeces for edible plants is criticised and recommended for fertilising ornamental plants or firewood crops and to use humus buildup from non-faecal sources for food crops (Buzie & Körner 2015; Yemaneh & Itchon 2015).

Case Studies

Urine has been used in agriculture for many years on a small-scale. In some developing countries, such as Ethiopia, Ghana, Rwanda and India, among others, there have been many projects which introduce ecological sanitation and the use of urine (but also faeces) in agriculture. Some of the experiences are summarised here:

A project conducted in 2010 in Arba Minch (Ethiopia) related to the Project 'Resource-Oriented Sanitation Concepts for Peri-Urban Areas in Africa' (ROSA) used urine to fertilise two maize crop trial sites. One of the trials showed a sevenfold increase in yield, compared to unfertilised soil. However, soil salinity also increased, which represents an issue in areas where irrigation water is scarce. In addition, experiences showed difficulties with collection, transport, treatment and reuse of urine, due to a lack of awareness of its advantages as fertiliser (Kassa, Meinzinger & Zewdie 2010).

Another pilot project was carried out in Nalanda District, Bihar State, India. This project focused on ecological sanitation systems for the use of human urine in crop production. The test showed that urine was at least as efficient as conventional NPK fertilisers. One of the main factors in changing farmers' ingrained attitudes about urine handling, was the annual savings of nearly US$ 72 per family using urine instead of commercial fertiliser.

According to Andersson (2014), to overcome social, political and strategic barriers, there has to be an open communication (including workshops and incentives) with key stakeholders, such as government representatives, local farmers, media and district representatives, as well as agricultural researchers and universities.

Furthermore, there have been many projects in Europe, especially in Germany, Sweden, Switzerland and Austria, promoting the use of urine as an alternative to mineral fertiliser (Boh 2013).

Conclusion

Urine is already proven as a fertiliser. Its quality and use depends on the particular social, economic and environmental characteristics of the location and application target. To avoid problems, utilisation of urine needs to be adapted to the local context and the needs of the users. The use of urine is not yet a conventional technology and as in every technology, there are advantages and disadvantages.

If not managed properly, the risk of pathogen transmission, as well as the risk of soil salinisation and strong and offensive odour can cause significant health problems and discomfort. Another disadvantage is the complicated transport, due to the high volume and weight of urine, especially in big-scale applications. Thus, it is important to know under which conditions urine can be used for agricultural purposes and to follow guidelines, so that there are no negative impacts (Eawag, Gensch & Spuhler n.d.).

The advantages of urine as a fertiliser are many, such as the recovery of nutrients, the reduced use of chemical fertilisers and freshwater resources, as well as the minimisation of wastewater and excreta contamination of surface and open waters. The use of urine contributes to self-sufficiency and food security. It is an easy and low-cost technique with monetary benefits for the user and can be used by anyone. The hygienic quality of urine is normally very high compared to faeces and the risk of pathogen transmission is low (Eawag, Gensch & Spuhler n.d.).

Finally, in urban areas, urine as a liquid fertiliser should be used on a small-scale to avoid the difficulties of transport and, through storage only, assure hygienic utilisation as fertiliser. The use of urine on a big scale can be foreseen in rural areas worldwide, with the additional advantage of contributing to public health, water savings and water pollution prevention in developing countries.

References

Andersson, K 2014, *Agricultural trials demonstrate benefits of urine harvesting and sustainable sanitation*, Stockholm Environment Institute, Stockholm, Sweden, viewed 7 April 2017, <http://www.susana.org/_resources/documents/default/2-2047-sei-fs-2014-biharecosan-bind.pdf>.

Antonini, S, Paris, S, Eichert, T & Clemens, J 2011, 'Nitrogen and Phosphorus Recovery from Human Urine by Struvite Precipitation and Air Stripping in Vietnam', *Clean - Soil, Air, Water*, vol. 39, no. 12, pp. 1099–104.

Behrendt, J, Arevalo, E, Gulyas, H, Niederste-Hollenberg, J, Niemiec, A, Zhou, J & Otterpohl, R 2002, 'Production of value added products from separately collected urine', *Water Science and Technology*, vol. 46, 6-7, pp. 341–6.

Behrendt, J, Winker, M, Anjonina, C, Blum, L, Buzie, C & Otterpohl, R 2009, 'Is the agricultural utilisation of treated urine and faeces recommendable?', in M Särkilahti, T Repka & J Penttinen (eds), *Dry Toilet 2009: 3rd International Dry Toilet Conference*, 3rd International Dry Toilet Conference, Tampere, Finland, 12-15 August 2009, Global Dry Toilet Association of Finland, pp. 63–8, viewed 19 September 2016, <https://www.tuhh.de/t3resources/aww/publikatio-nen/pdf/DT2009AgriculturalUtilisationTreatedUrineFaecesRecommendable.pdf>.

Boh, MY 2013, 'Human urine as a crop fertilizer under saline conditions', Dissertation, University of Hohenheim, Stuttgart, Germany, viewed 21 September 2016, <http://opus.uni-hohen-heim.de/volltexte/2014/932/pdf/PhD_Dissertation_Michael_Yongha_Boh.pdf>.

Buzie, C & Körner, I 2015, 'Composting of Bioresources for Terra Preta-inspired Products', in Deutsche Bundesstiftung Umwelt (ed.), *Terra Preta Sanitation: Backgrounds, principles and innovations*, Deutsche Bundesstiftung Umwelt, Osnabrück, Germany, pp. 86–119.

Clemens, J, Nisipeanu, P, Muskolus, A, Rieß, P, Arnold, U, Vinnerås, B & Winker, M 2008, 'Produkte aus neuartigen Sanitärsystemen in der Landwirtschaft' (German), *KA - Korrespondenz Abwasser, Abfall*, vol. 55, no. 10, pp. 1120–5.

Eawag, Gensch, R & Spuhler, D n.d., *Urine Fertilisation: Small-scale*, Sustainable Sanitation and Water Management, viewed 1 April 2017, <http://www.sswm.info/category/implementation-tools/reuse-and-recharge/hardware/reuse-urine-and-faeces-agriculture/urine-f>.

Eawag, Wafler, M & Spuhler, D n.d., *UDDT*, Sustainable Sanitation and Water Management, viewed 26 May 2017, <https://www.sswm.info/category/implementation-tools/water-use/hardware/toilet-systems/uddt>.

Gajurel, DR, Gulyas, H, Reich, M & Otterpohl, R n.d., 'Behavior of four selected pharmaceuticals during log-time storage of yellow water', in *Ecosanlac – Food and Water Security*, viewed 21 September 2016, <https://www.tuhh.de/t3resources/aww/publikationen/pdf/Gajurel_etal.pdf>.

Haq, G & Cambridge, H 2012, 'Exploiting the co-benefits of ecological sanitation', *Current Opinion in Environmental Sustainability*, vol. 4, no. 4, pp. 431–5.

Jönsson, H, Richert Stintzing, A, Vinnerås, B & Salomon, E 2004, *Guidelines on the use of urine and faeces in crop production*, EcoSanRes Publication Series, 2nd edn, Stockholm, Sweden, viewed 9 March 2016, <http://www.ecosanres.org/pdf_files/ESR_Publications_2004/ESR2web.pdf>.

Karak, T & Bhattacharyya, P 2011, 'Human urine as a source of alternative natural fertilizer in agriculture: A flight of fancy or an achievable reality', *Resources, Conservation and Recycling*, vol. 55, no. 4, pp. 400–8.

Kassa, K, Meinzinger, F & Zewdie, W 2010, 'Experiences from the use of urine in Arba Minch, Ethiopia: Sustainable Sanitation Practice', *Sustainable Sanitation Practice*, no. 3, pp. 12–7.

Miso, A & Spuhler, D n.d., *Fertiliser from Urine: Struvite*, Sustainable Sanitation and Water Management, viewed 6 April 2017, <http://www.sswm.info/category/implementation-tools/reuse-and-recharge/hardware/reuse-urine-and-faeces-agriculture/fertili>.

Möllring, B 2003, 'Toiletten und Urinale für Frauen und Männer: Die Gestaltung von Sanitärobjekten und ihre Verwendung in öffentlichen und privaten Bereiche' (German), Dissertation, Universität der Künste Berlin, Berlin, Germany.

Richert, A, Jönsson, H, Schönning, C, Hinkkanen, K, Kvarnström, E, Ganrot, Z, Samwel, M, Gabizon, S & Mohr, A 2007, *Urine diverting toilets in climates with cold winters: Technical considerations and the reuse of nutrients with a focus on legal and* *hygienic aspects*, Women in Europe for a Common Future, Munich, viewed 9 January 2016, <http://www.susana.org/_resources/documents/default/2-807-urine-diverting-toilets-in-climates-with-cold-winters1.pdf>.

Rieck, C, Münch, E von & Hoffmann, H 2012, *Technology review of Urine-diverting Dry Toilets (UDDTs): Overview on design, management, operation and costs*, Deutsche Gesellschaft für internationale Zusammenarbeit (GIZ) GmbH, Eschborn, Germany, viewed 4 January 2017, <http://www.susana.org/en/resources/library/details/874>.

Soria Akut, PD 2014, 'Resource oriented sanitation concepts for poor rural and peri-urban communities in tropical climates: a case of Cagayan de Oro City, Misamis Oriental and Bukidnon, Philippines', Master Thesis, Hamburg University of Technology, Hamburg, Germany, viewed 21 September 2016, <https://www.tuhh.de/t3resources/aww/publikationen/pdf/dipl/MT_Peter_Akut20140407.pdf>.

Tettenborn, F 2012, 'Aspects of systems for separate urine collection and treatment: Selected techniques and potential implementation in an urban context', Dissertation, Hamburg University of Technology, Hamburg, Germany, viewed 4 January 2018, <http://tubdok.tub.tuhh.de/handle/11420/1042>.

Tettenborn, F, Behrendt, J & Otterpohl, R 2008, 'Pharmaceutical residues in source separated urine and their fate during nutrient-recovery processes', in IWA (ed.), *6th IWA World Water Congress and Exhibition*, Vienna, Austria, 6-12 September, International Water Association, viewed 16 January 2018, <https://www.tuhh.de/t3resources/aww/publikationen/pdf/TETT08A.pdf>.

Tilley, E, Ulrich, L, Lüthi, C, Reymond, P & Zurbrügg, C 2014, *Compendium of sanitation systems and technologies*, 2nd edn, Swiss Federal Institute of Aquatic Science and Technology, Duebendorf, Switzerland, viewed 9 March 2016, <http://www.eawag.ch/en/department/sandec/publikationen/compendium/>.

Uchida, R 2000, 'Essential Nutrients for Plant Growth: Nutrient Functions and Deficiency Symptoms', in JA Silva & RS Uchida (eds), *Plant Nutrient Management in Hawaii's Soils: Approaches for Tropical and Subtropical Agriculture*, College of Tropical Agriculture and Human Resources, University of Hawaii at Manoa, Honolulu, Hawaii, pp. 31–55.

Udert, K, Bucley, C, Wächter, M, McArdell, C, Kohn, T, Strande, L, Zöllig, H, Fumasoli, A, Oberson, A & Etter, B 2015, 'Technologies for the treatment of source-separated urine in the eThekwini Municipality', *Water SA*, vol. 41, no. 2, pp. 212–21.

UN 2010, *The human right to water and sanitation: A/RES/64/292*, United Nations General Assembly, viewed 16 January 2018, <http://www.un.org/en/ga/search/view_doc.asp?symbol=A/RES/64/292>.

——2015, *The millennium development goals report*, United Nations Development Programme, New York, viewed 4 January 2018, <http://www.un.org/millenniumgoals/2015_MDG_Report/pdf/MDG%202015%20rev%20(July%201).pdf>.

——2017, 'At start of World Water Week, UN Assembly President says water and sanitation goals need major push', *UN News Centre*, 28 August, viewed 21 September 2017, <http://www.un.org/apps/news/story.asp?NewsID=57423#.WcPIpnRpHcs>.

UN-Water 2016, *Water and sanitation interlinkages across the 2030 Agenda for Sustainable Development*, Geneva, Switzerland, viewed 4 January 2018, <http://www.unwater.org/publications/water-sanitation-interlinkages-across-2030-agenda-sustainable-development/>.

WHO 2006, *Excreta and greywater use in agriculture*, WHO guidelines for the safe use of wastewater, excreta and greywater, vol. 4, World Health Organization, Geneva, Switzerland.

Winblad, U & Simpson-Hébert, M (eds) 2004, *Ecological sanitation: Revised and enlarged edition*, 2nd edn, Stockholm Environment Institute (SEI), Stockholm, Sweden.

Winker, M 2009, 'Pharmaceutical residues in urine and potential risks related to usage as fertiliser in agriculture', Dissertation, Hamburg University of Technology, Hamburg, Germany, viewed 21 September 2016, <http://nbn-resolving.de/urn:nbn:de:gbv:830-tubdok-5575>.

Winker, M, Dimova, D, Ritter, K, Otterpohl, R & Clemens, J 2010, 'Effect of five pharmaceutical substances contained in urine on the germination of cress and cereal seedlings', *Sustainable Solutions for Small Water and Wastewater Treatment Systems (S2Small2010)*, IWA Conference, Girona, Spain, 19-22 April 2010.

Yemaneh, A & Itchon, G 2015, 'Stabilization and hygienization of organic matter', in Deutsche Bundesstiftung Umwelt (ed.), *Terra Preta Sanitation: Backgrounds, principles and innovations*, Deutsche Bundesstiftung Umwelt, Osnabrück, Germany, pp. 120–33.

A Review of Terra Preta Sanitation with a Focus on the Research Outcomes of the Institute of Wastewater Management and Water Protection (AWW)

Dario Fröndhoff and Ruth Schaldach

'We have taken soils for granted for a long time.
Nevertheless, soils are the foundation of food production and food security.'

José Graziano Da Silva, Food and Agriculture Organization of the United Nations Director-General (FAO & ITPS 2015, XIX)

Please cite as: Fröndhoff, D & Schaldach, R 2018, 'A Review of Terra Preta Sanitation with a Focus on the Research Outcomes of the Institute of Wastewater Management and Water Protection (AWW)' in R Schaldach & R Otterpohl (eds), RUVIVAL Publication Series, vol. 3, Hamburg, pp. 19 – 29, <http://nbn-resolving.de/urn:nbn:de:gbv:830-88218207>.

Abstract

Terra Preta Sanitation (TPS) is an astonishing biowaste/sanitation system from a highly advanced ancient culture. It shows great potential for soil building and nutrient recycling from excreta. TPS was and is developed based on a rediscovered historic practice. TPS systems treat excreta and produce valuable soil amendments. Such sanitation systems can contribute to attaining particular Sustainable Development Goals. Findings of highly fertile soils in the Amazon region initiated research in this field of study. Archaeological research revealed that Terra Preta was produced from biowaste and excreta with charcoal additives and layers of pieces from broken ceramic. The Institute of Wastewater Management and Water Protection (AWW) at Hamburg University of Technology (TUHH) conducted research on lactic acid fermentation (LAF) and vermicomposting, with a special focus on sanitisation and process conditions. The AWW performed case studies in India, the Philippines and Ethiopia and developed implementation strategies for conventional and new sanitation systems. Moreover, the Institute facilitated the design of a container toilet for Terra Preta Sanitation, which is adjusted to different cultural requirements. LAF can make the collection over longer timespans odour free and sanitised at the same time. The downside is a demand for a sugar additive, however, this can be solved by the addition of biowaste. This literature review gives an overview of the current state of research conducted at the Institute of Wastewater Management and Water Protection (AWW) at the Hamburg University of Technology.

Keywords: *Terra Preta Sanitation, lactic acid fermentation, vermicomposting, dry sanitation, literature review*

Introduction

Sustainable utilisation of natural resources is nowadays a central challenge and this is also reflected in food security and waste management. On the one hand, soils are depleted and nutrient rich humus is extracted due to extensive agriculture, while on the other, conventional sanitation systems are not equipped to recycle precious nutrients and give them back to the soil. One way to address this could be a rediscovered sanitation system from the Amazon region called Terra Preta (Portuguese for 'dark soil'). Originally, this technique consists of urine diversion, lactic acid fermentation (LAF) with charcoal additives and subsequent vermicompostation by earthworms. LAF suppresses odour formation and sanitises the excreta. Subsequent composting and vermicomposting additionally sanitise the substrate and nutrient rich humus is produced (Factura et al. 2010). This product can be utilised as soil amendment for non-food purposes in forestry or agriculture (Buzie & Körner 2015).

In recent years, there has been ongoing research on the Terra Preta solution at the Institute for Wastewater Management and Water Protection (AWW) at Hamburg University of Technology (TUHH) among others (Alepu Odey et al. 2017; De Gisi, Petta & Wendland 2014; Schuetze & Santiago-Fandiño 2014) and since 2013 a biyearly Terra Preta Sanitation (TPS) conference (TPS-Initiative 2015). AWW has been working on resource-oriented sanitation (also called ecological sanitation), both high-tech and low-tech, since around 20 years. AWW examined the Terra Preta approaches intensively, operated case studies, developed implementation strategies and facilitated the design of a container toilet suitable for TPS.

Lactic Acid Fermentation

Lactic acid fermentation is the first treatment step in TPS after the collection of faeces. LAF shows several positive effects, such as efficient odour suppression, significant pathogen reduction, as well as conservation of nutrients and organic matter (Yemaneh et al. 2012). This fermentation process has been researched in terms of sanitisation degree and in terms of appropriate process conditions. LAF makes container toilets without biocides possible – these are far simpler than the alternative of urine-diverting dry toilets (UDDT).

Sanitisation

The sanitisation degree of the feedstock is crucial for the subsequent application of the products (Buzie & Körner 2015). Ample research has been conducted on this topic and the research results are summarised in Table 1 (p. 21).

The research undertaken by Factura et al. (2010) demonstrates general sanitisation achievements of the TPS process, while Yemaneh et al. (2012) conducted more specific research concerning sanitisation in the LAF stage. Yemaneh et al. (2012) monitored *E. coli* as the Sanitation Indicator Bacteria and concluded that complete elimination is achieved in this process.

Table 1 LAF Sanitation

Authors	Micro-organisms	Degree of elimination
Yemaneh et al. (2012)	*E. Coli*	Complete elimination after 5 (resp. 21) days with addition of 10 % (5 %) molasses
Yemaneh et al. (2014)	*E. Coli*	Complete elimination after 21 days with addition of 50 % kitchen bio waste
Factura et al. (2014)	*Ascaris* eggs	50 % reduction after 30 days, complete reduction after 60 days
	Taenia and *Trichuris trichura*	Complete reduction after 30 days

Further research by Yemaneh et al. (2014) confirmed the removal of *E. coli* bacteria by LAF. In both cases, the *E. coli* colonies were determined using ChromoCult Coliform Agar. Factura et al. (2014) demonstrated in a field study a reduction of up to 50 % of *Ascaris* eggs (complete reduction after 60 days) and found no *Taenia* and *Trichuris trichura* bacteria after 30 days. Yemaneh & Itchon (2015) emphasise that low pH values, due to lactic acid formation eliminate pathogenic microorganisms and antimicrobial compounds formed by lactic acid bacteria, contribute to sanitisation. Furthermore, Yemaneh & Itchon (2015) refer to publications that examine inhibition of pathogenic microorganisms besides *E. coli*.

Process Conditions

Factura et al. (2010) conducted basic research on LAF process conditions. Analyses to improve these process conditions were undertaken by Yemaneh et al. (2012). The authors researched suitable microbial inoculants, differing sugar supplements and modes of excreta collection. The process conditions were assessed based on the pH value, odour, *E. coli* and lactic acid formation. A summary of LAF process conditions and adjustment recommendations is given in Table 2.

Table 2 Process conditions

Authors	Process parameters	Adjustment
Factura et al. (2010)	Charcoal additives	Charcoal (75 %), stone dust (16 % $CaCO_3$) and forest soil (9 %)
	Charcoal additives to faecal matter ratio as percentage of wet matter	Percentage of wet matter from 24 – 17 %
Yemaneh et al. (2012)	Lactic acid bacteria	*Lactobacillus plantarum, Lactobacillus casei* and *Pediococcus acidilactici*
	Sugar supplement	10 % (w/w) molasses
	Charcoal	10 % (w/w) charcoal
	Microbial inoculant	10 % (w/w) Lactic Acid Bacteria inoculant
Yemaneh et al. (2014)	Sugar supplement	40 – 50 % (w/w) kitchen waste as low cost molasses alternative

Yemaneh et al. (2012) concluded that the suitable microbial inoculant consisted of three lactic acid bacteria (*Lactobacillus plantarum, Lactobacillus casei* and *Pediococcus acidilactici*) and that the optimal sugar supplement proportion was 10 % mass fraction of molasses. Finally, they concluded that LAF is a viable solution for all tested collection modes (combined and partially combined collection). Yemaneh et al. (2014) further assessed the usage of kitchen waste as a low-cost sugar supplement. They state that the application of kitchen waste, with a mass fraction of 40 – 50 % in regard to wet weight of faecal matter, is appropriate as a low-cost sugar supplement. This study evaluated additional parameters: the total amount of soluble nitrogen and ammonium nitrogen in the substrate during LAF. The findings of Yemaneh et al. (2014) regarding nitrogen compounds can hardly be compared to the findings of Factura et al. (2010) due to the usage of different inoculants and additives. However, it needs to be noted that most studies (Factura et al. 2010; Prabhu et al. 2014b) indicate an increase in ammonia (and ammonium respectively) independently from the chosen lactic acid bacteria after LAF, in contrast to the findings of Yemaneh et al. (2014).

LAF is well researched in terms of sanitisation regarding *E. coli* bacteria (Scheinemann et al. 2015; Yemaneh et al. 2014; Yemaneh & Itchon 2015). Other research concerning pathogen elimination could be conducted. LAF operates well and shows satisfying results in odour suppression and stabilisation of organic matter (Factura et al. 2010).

Vermicomposting

The process of vermicomposting is subsequent to LAF. This composting technique aims to reduce pathogens and to contribute to a stable product through the digestion of the pre-fermented substrate by earthworms. Research reveals different results regarding the sanitisation degree and examines suitable process conditions.

Sanitisation through Vermicomposting

As mentioned in the previous chapter, the degree of sanitisation of the feedstock is crucial for the subsequent application of the products (Buzie & Körner 2015). A general sanitisation degree within TPS was demonstrated by Factura et al. (2010). Buzie (2010) evaluated the feasibility of the vermicomposting technology as a method for faecal matter sanitisation and state on the basis of Sanitation Indicator Bacteria that the sanitisation of faecal matter with and without earthworms mostly results in pathogen decline. Earthworms lead to higher pathogen reduction (Buzie 2010). Based on United States Environmental Protection Agency (EPA) guidelines for use of biosolids (EPA 1999), the end-products are rated as sanitisation Class B. Buzie (2010) give a comprehensive background to the process of vermicomposting. Stöckl et al. (2014) assess the sanitisation of faecal matter during vermicomposting, especially concerning *Salmonella*. It is shown that acidification contributes to *Salmonella london* elimination and thermal sanitisation is more efficient than the digestion of earthworms (Stöckl et al. 2014). While Buzie (2010) promotes limited use of end-products, Stöckl et al. (2014) are more strict and do not recommend vermicomposting as a safe method for sanitisation regarding *Salmonella*. The authors recommend further studies to enhance the vermicomposting technique or prior sanitisation (see LAF sanitisation). Walter et al. (2014) examine microorganisms at certain levels of vermicomposting phases. The study un-

Table 3 Sanitisation through vermicomposting

Authors	Microorganisms	Degree of elimination
Buzie (2010)		*Earthworm participation vs. composting process*
	E. Coli	99.98 % vs. 45.46 % reduction
	Faecal coliforms	99.98 % vs. 49.26 % reduction
	Enterococcus faecalis	99.99 % reduction vs. 24.72 % increase
	Salmonella spp	99.76 % vs. 74.57 % reduction
	Shigella spp	99.69 % vs. 99.71 % reduction
	Enterobacter spp	99.98 % vs. 56.81 % reduction
Factura et al. (2014)	Parasite ova	Zero presence
Stöckl et al. (2014)	*Salmonella*	No complete reduction after 88 days due to vermicomposting
Microarray technology analyses concerning the absence or presents of microorganisms:		
Walter et al. (2014)	*Acinetobacter*	Absent in EM and RM sample
	Enterococcus sp.	Present after 33 days, absent after 88 days
	Flavobacteria	Absent in EM and RM sample
	Pseudomonas	Absent in EM and RM sample
	Salmonella sp.	Present after 33 days, absent after 88 days
	Stenotrophomonas maltophilia	Present
	Xanthomonas	Present
	Xylella	Present

EM: Effective Microorganisms
RM: Reckin Laboratory Mix

derlines the concerns regarding remaining pathogens after vermicomposting for 88 days. Factura et al. (2014) demonstrate in a field study an elimination of parasite ova after the vermicomposting process with prior LAF. The main research results are summarised in Table 3. Buzie & Körner (2015) insist explicitly that faecal matter (vermi-) composts should not be used for food production due to sanitisation insecurity.

Process Conditions

The process conditions of vermicomposting were investigated by several authors (see Table 4, p. 24).

Buzie (2010) conducted research on process conditions for vermicomposting. Earthworms (*Eisenia fetida/foetida*) were intoxicated by human faeces as a consequence of the high nutrient content of excreta, ammonia production and anaerobic conditions (Buzie 2010). Buzie (2010) recommend 70 % moisture content and temperatures between 20 – 25°C as optimal. The authors propose further research on the carbon-to-nitrogen ratio (C/N ratio). Factura et al. (2010) came to similar results and aim to improve the environmental conditions by adding bulking agents like wood chips or paper, to raise the C/N ratio.

Table 4 Process conditions of vermicomposting

Authors	Process parameter	Adjustment
Buzie (2010)	Moisture content	70 %
	Tempera-ture	20 – 25°C
	C/N ratio	20 – 25
Betten-dorf, Stöckl & Otterpohl (2014)	C/N ratio	31.5 (calculated on molar base)
	Mixture of raw material 1*	FM: 35 % sludge, 22 % E0-earth, 19 % grass, 13 % OFV, 3 % Wood, 9 % charcoal
	Mixture of raw material 2*	FM: 32 % sludge, 20 % E0-earth, 18 % grass, 12 % OFV, 3 % Wood, 15 % char-coal
Factura et al. (2014)	C/N ratio	70:30 (equals 2.3)
Walter et al. (2014)	Micro-organisms	EM and RM have no substantial effect on starter communities

C/N ratio: carbon-to-nitrogen ratio
FM: faecal matter
OFV: overlaid fruits and vegetables
EM: Effective Microorganisms
RM: Reckin Laboratory Mix

**Readout from Bettendorf, Stöckl & Otterpohl (p. 4, Figure 2); percentage in weight fraction (w/w)*

Bettendorf, Stöckl & Otterpohl (2014) conducted experiments with a varying mixture of raw materials for vermicomposting and adjusted the molar C/N ratio to 31.5. Raw materials used are faecal sludge, charcoal, grass, wood, overlaid fruits and vegetables and pot soil. The aim of the experiments is to evaluate the vermicomposting process in terms of physio-chemical product characteristics dependent on raw composition. Bettendorf, Stöckl & Otterpohl (2014) show that the vermi-composted product based on their raw composition is a stabilised and fertile soil enhancer.

A study conducted by Walter et al. (2014) evaluates the effects of amended starter communities by two microorganism colonies (Effective Microorganisms and Reckin Laboratory Mix). It is indicated that the deployed microorganisms have no substantial effects on starter communities. Walter et al. (2014) recommend the characterisation of the whole microbial community to gain a deeper understanding of the composting process in TPS. Buzie & Körner (2015) give a comprehensive overview on composting and vermicomposting. A wide range of feedstock is presented, sanitisation is discussed, (vermi-) composting techniques are explained and a concluding comparison of the two techniques is drawn (Buzie & Körner 2015).

Research shows varying results in terms of sanitisation success. Further research on sanitisation is advised (Stöckl et al. 2014; Walter et al. 2014). Vermicomposting process conditions have been improved through further research. The vermicomposting process produces matured compost that serves as a valuable soil enhancer (Bettendorf, Stöckl & Otterpohl 2014). However, Buzie & Körner (2015) do not recommend Terra Preta product utilisation for food production. One major advantage in TPS is the combination of two sanitisation steps.

Implementation of the Terra Preta System

The Terra Preta System is an integrated system and consists of more than LAF and vermicomposting. The implementation in terms of practical application in different regions and climates is necessary to prove reliability and to spread the idea of TPS. Furthermore, research on the theoretical opportunities to implement TPS to conventional and new systems is crucial to provide strategies that can be integrated into existing structures. TPS offers many options and can also in the simplest form consist of sealed pit latrines put into LAF and regular collection.

Following general studies on TPS (Factura et al. 2010) and its single constitutes (Buzie 2010; Yemaneh et al. 2012), further studies were carried out by Bulbo et al. (2014), Factura et al. (2014), Prabhu et al. (2014b) and Yemaneh, Bulbo & Otterpohl (2015) in order to test the feasibility of implementation of these systems. Various case studies were conducted to this end and a summary of some of their findings will be provided in the following subchapters.

Case Study in Goa, India

Prabhu et al. (2014b) tested TPS as an alternative solution for the management of primary sludge from the Birla Institute in Goa, India. Experimental setups with varying raw material compositions based on the research of Factura et al. (2010) were conducted. Raw materials used were sludge, charcoal, Effective Microorganisms, soil and calcium carbonate ($CaCO_3$). In the vermicomposting phase, earthworms died due to ammonia toxicity. The addition of dry grass cuttings kept the subsequently new added worms alive. As a result, Prabhu et al. (2014b) stated that Terra Preta can be produced from primary sewage sludge. Contrary to Factura et al. (2010), Prabhu et al. (2014b) negate the necessity to separate urine and faeces. Prabhu et al. (2014b) do not give a recommendation for the most suitable raw material composition. In a different study, the effects of the produced Terra Preta on the growth of *Vigna radiate* are assessed by Prabhu et al. (2014a). The experiments showed an increase in plant growth when Terra Preta is applied to soil in comparison to untreated soil (Prabhu et al. 2014a).

Case Study in Cagayan de Oro, the Philippines

Factura et al. (2014) tested TPS system implementation in the tropical region of Cagayan de Oro in the Philippines. In this project, UDDTs with monthly collection were installed. The collected faeces was kept in storage facilities where they were protected from heat and moisture (Factura et al. 2014). Households use the collected urine in their backyards as fertiliser. Corncobs were added to adjust the C/N ratio to 2.3 to assure suitable conditions for vermicomposting. This differs significantly from the research of Bettendorf, Stöckl & Otterpohl (2014). Factura et al. (2014) concluded that TPS is effective in counteracting odours and providing a hygienically safe product for agricultural application.

Case Study in Arba Minch, Ethiopia

Bulbo et al. (2014) studied the availability of precursors in Arba Minch (Ethiopia) to implement TPS. These precursors are human urine, faeces, biomass waste, manure, bones, biochar and process organisms. It is indicated that the limiting precursor for the TPS system in Arba Minch is charcoal. To enhance the availability of biochar, Bulbo et al. (2014) recommend further studies on the conversion of solid waste into biochar and the dual use of cooking stoves to produce biochar. Moreover, Bulbo et al. (2014) point to the high potential of TPS to improve the soil and enhance reforestation in the region. Evaluation of the microbiological quality of the end-product should be conducted in the future (Bulbo et al. 2014). Yemaneh, Bulbo & Otterpohl (2015) presented their results concerning resource recovery and economic aspects of TPS in Arba Minch at the 2015 RANMIRAN conference (ed. Körner 2015). Yemaneh, Bulbo & Otterpohl (2015) concluded that the TPS system produces a nutrient and organic matter rich vermicompost. Furthermore, biogas formed from human waste can be collected and utilised. Yemaneh, Bulbo & Otterpohl (2015) picked up the idea of Bulbo et al. (2014) to install wood stoves that produce biochar. It is deduced that fertiliser, soil conditioner and energy result in net benefit regarding monetary value (Yemaneh, Bulbo & Otterpohl 2015).

Theoretical Implementation

Bettendorf, Wendland & Schuetze (2015) give a comprehensive overview of the subject matter and the integration of TPS. The wastewater streams separated by source are discussed. Furthermore, domestic wastewater flows and loads are exhibited. Moreover Bettendorf, Wendland & Schuetze (2015) discuss transport and collection systems of conventional and new systems. Finally, the implementation of TPS systems to conventional and new systems was examined. Tangible new system implementations are Blackwater Vacuum System, Dry Toilet System and 'Loo-loop' System (Bettendorf, Wendland & Schuetze 2015).

TPS is implemented in different regions with success regarding feasibility and outcome of the final product. However, TPS faces limiting factors, such as the limited presence of charcoal. New concepts to implement TPS to existing systems are available. Application to new systems has been proven in pilot projects (Bettendorf, Wendland & Schuetze 2015).

Loolaboo – Terra Preta Toilet

The AWW institute facilitated an international toilet design award together with the World Toilet Organisation in 2012 with a total prize of US$ 50,000. The winner was Sabine Schober from the Triften design studio with the Terra Preta toilet – Loolaboo (TPS-Initiative 2017). By enabling the user to either sit or squat on the toilet, the design is culturally acceptable worldwide (TPS-Initiative 2017). Figure 1 shows the award winning design.

Figure 1 Loolaboo - Terra Preta Toilet (TPS-Initiative 2017)

Loolaboo meets the requirements for the TPS system, since low amounts of water from a spray nozzle are required and LAF takes place in the storage tank (TPS-Initiative 2017). The tank is accessible through a hole in the back and a sliding mechanism seals the toilet (Otterpohl 2012; TPS-Initiative 2017).

Conclusion

Terra Preta Sanitation addresses several Sustainable Development Goals and has the potential to contribute to their success. Nevertheless, further research needs to be conducted.

Both process steps and implementation strategies of TPS are researched at the AWW institute of TUHH. Results indicate that TPS is a promising rediscovered ancient technology that closes the loop between sanitation issues and soil amendment. LAF can be designated a stable process and vermicomposting was also analysed in detail with satisfying results. Several case studies proved a well-functioning implementation in different areas. However, as long as Terra Preta is not entirely proven to be hygienically safe, the products should not be used on soils where food production is taking place. Studies that demonstrate a large-scale integration of TPS in conventional systems could be a future field of research. A strategic objective could be to raise public awareness of the fact that as much as a third of the total land is moderately to highly degraded and that 2.4 billion people lack improved facilities. Education is an important means of achieving broader acceptance.

Picture Credits

Figure 1 (p. 26) Loolaboo - Terra Preta Toilet
Source: TPS-Initiative (2017)

References

Alepu Odey, E, Li, Z, Zhou, X & Kalakodio, L 2017, 'Fecal sludge management in developing urban centers: a review on the collection, treatment, and composting', *Environmental Science and Pollution Research*, vol. 24, pp. 23441–52.

Bettendorf, T, Stöckl, M & Otterpohl, R 2014, 'Vermicomposting of municipal solid organic waste and fecal matter as part of Terra Preta Sanitation: A process and product assessment', in T Bettendorf, C Wendland & Otterpohl (eds), *Terra Preta Sanitation*, 1st International Conference on Terra Preta Sanitation, Hamburg, Germany, 28-31 August 2013, Deutsche Bundesstiftung Umwelt, viewed 10 January 2018, <https://www.tuhh.de/t3resources/aww/publikationen/pdf/TPS-IC/21_T_Bettendorf_et_al.pdf>.

Bettendorf, T, Wendland, C & Schuetze, T 2015, 'Terra Preta Sanitation Systems and Technologies', in Deutsche Bundesstiftung Umwelt (ed.), *Terra Preta Sanitation: Backgrounds, principles and innovations*, Deutsche Bundesstiftung Umwelt, Osnabrück, Germany, pp. 62–85.

Bulbo, M, Yemaneh, A, Amlaku, T & Otterpohl, R 2014, 'Assessment of availability of Terra Preta Sanitation precursors in Arba Minch, Ethiopia', in T Bettendorf, C Wendland & Otterpohl (eds), *Terra Preta Sanitation*, 1st International Conference on Terra Preta Sanitation, Hamburg, Germany, 28-31 August 2013, Deutsche Bundesstiftung Umwelt, viewed 6 December 2017, <https://www.tuhh.de/t3resources/aww/publikationen/pdf/TPS-IC/11_Bulbo_et_al.pdf>.

Buzie, C 2010, 'Development of a continuous single chamber vermicomposting toilet with urine diversion for on-site application', Dissertation, Hamburg University of Technology, Hamburg, Germany, viewed 6 December 2017, <https://doi.org/10.15480/882.1001>.

Buzie, C & Körner, I 2015, 'Composting of Bioresources for Terra Preta-inspired Products', in

Deutsche Bundesstiftung Umwelt (ed.), *Terra Preta Sanitation: Backgrounds, principles and innovations*, Deutsche Bundesstiftung Umwelt, Osnabrück, Germany, pp. 86–119.

De Gisi, S, Petta, L & Wendland, C 2014, 'History and Technology of Terra Preta Sanitation', *Sustainability*, vol. 6, no. 11, pp. 1328–45.

EPA 1999, *Biosolids Generation, Use, and Disposal in The United States*, United States Environmental Protection Agency, viewed 25 January 2018, <https://www.epa.gov/sites/production/files/2015-07/documents/biosolids_generation_use_disposal_in_u.s_1999.pdf>.

Factura, H, Bettendorf, T, Buzie, C, Pieplow, H, Reckin, J & Otterpohl, R 2010, 'Terra Preta sanitation: Re-discovered from an ancient Amazonian civilisation - integrating sanitation, bio-waste management and agriculture', *Water Science & Technology*, vol. 61, no. 10, pp. 2673–9.

Factura, H, Medalla, J, Masgon, M, Miso, A, Itchon, G, Buzie, C, Gensch, R & Otterpohl, R 2014, 'The Implementation and Practices of Terra Preta Sanitation in the Tropics: The Experiences from Xavier University Ateneo de Cagayan, Cagayan de Oro City, Philippines', in T Bettendorf, C Wendland & Otterpohl (eds), *Terra Preta Sanitation*, 1st International Conference on Terra Preta Sanitation, Hamburg, Germany, 28-31 August 2013, Deutsche Bundesstiftung Umwelt, viewed 10 January 2018, <https://www.tuhh.de/t3resources/aww/publikationen/pdf/TPS-IC/03_H_Factura_et_al.pdf>.

FAO & ITPS 2015, *Status of the World's Soil Resources: Main Report*, Food and Agriculture Organization of the United Nations & Intergovernmental Technical Panel on Soils, Rome, Italy, viewed 6 December 2017, <http://www.fao.org/3/a-i5199e.pdf>.

Körner, I (ed.) 2015, *RAMIRAN 2015: 16th International Conference, Rural-Urban Symbiosis*, Hamburg, Germany, 8.-10. September, Hamburg University of Technology, viewed 6 December 2017, <https://doi.org/10.15480/882.1297>.

Otterpohl, R 2012, *The 2012 WTO International Toilet Design Award in Durban: Winner is Sabine Schober from Hamburg, Germany*, viewed 4 January 2017, <http://www.terra-preta-sanitation.net/cms/index.php?id=19>.

Prabhu, M, Horvat, M, Lorenz, L, Otterpohl, R, Bettendorf, T & Mutnuri, S 2014a, 'Effect of terra preta compost on growth of Vigna radiate', in T Bettendorf, C Wendland & Otterpohl (eds), *Terra Preta Sanitation*, 1st International Conference on Terra Preta Sanitation, Hamburg, Germany, 28-31 August 2013, Deutsche Bundesstiftung Umwelt, viewed 10 January 2018, <https://www.tuhh.de/t3resources/aww/publikationen/pdf/TPS-IC/04_Prabhu_et_al.pdf>.

——2014b, 'Terra Preta as an Alternative for the Management of Sludge from Wastewater Treatment Plants', in T Bettendorf, C Wendland & Otterpohl (eds), *Terra Preta Sanitation*, 1st International Conference on Terra Preta Sanitation, Hamburg, Germany, 28-31 August 2013, Deutsche Bundesstiftung Umwelt, viewed 10 January 2018, <https://www.tuhh.de/t3resources/aww/publikationen/pdf/TPS-IC/07_Prabhu_et_al.pdf>.

Scheinemann, HA, Dittmar, K, Stöckel, FS, Müller, H & Krüger, ME 2015, 'Hygienisation and Nutrient Conservation of Sewage Sludge or Cattle Manure by Lactic Acid Fermentation', *PLoS ONE*, vol. 10, no. 3.

Schuetze, T & Santiago-Fandiño, V 2014, 'Terra Preta Sanitation: A Key Component for Sustainability in the Urban Environment', *Sustainability*, vol. 6, no. 11, pp. 7725–50.

Stöckl, M, Roggentin, P, Bettendorf, T & Otterpohl, R 2014, 'Assessment of hygienisation of faecal matter during terra preta inspired vermicomposting by qualitative identification of Salmonella spec.', in T Bettendorf, C Wendland & Otterpohl (eds), *Terra Preta Sanitation*, 1st International Conference on Terra Preta Sanitation, Hamburg, Germany, 28-31 August 2013, Deutsche Bundesstiftung Umwelt, viewed 10 January 2018, <https://www.tuhh.de/t3resources/aww/publikationen/pdf/TPS-IC/17_Stoeckl_et_al.pdf>.

TPS-Initiative 2015, *2nd International Terra Preta Sanitation Conference at Birla Institute of Technology & Science, Goa, India*, Hamburg University of Technology, viewed 25 January 2018, <http://www.terra-preta-sanitation.net/cms/index.php?id=61>.

——2017, *loolaboo: The Terra Preta Toilet*, viewed 4 January 2017, <http://www.loolaboo.com/>.

Walter, A, Bettendorf, T, Stöckl, M, Franke-Whittle, I & Insam, H 2014, 'Screening of the microbial community in charcoal and microbe- amended vermicomposts', in T Bettendorf, C Wendland & Otterpohl (eds), *Terra Preta Sanitation*, 1st International Conference on Terra Preta Sanitation, Hamburg, Germany, 28-31 August 2013, Deutsche Bundesstiftung Umwelt, viewed 10 January 2018, <https://www.tuhh.de/t3resources/aww/publikationen/pdf/TPS-IC/18_Walter_et_al.pdf>.

Yemaneh, A, Bulbo, M, Factura, H, Buzie, C & Otterpohl, R 2012, 'Development of systems for waterless collection of human excreta by application of lactic acid fermentation process in terra preta sanitation', *4th International Dry Toilet Conference*, Tampere, Finland, 22-24 August 2012, DRY TOILET 2012, viewed 10 January 2018, <http://www.susana.org/_resources/documents/default/2-1618-41-development-of-system-for-waterless-collection-of-human-excretalactic-acid-fermentation-processterra-preta-a-yemaneh-m-bulbo-h-factura-c-buzie-r-otterpohl.pdf>.

Yemaneh, A, Bulbo, M & Otterpohl, R 2015, 'Resources recovery and economic aspects in the application of terra preta sanitation system in Arba Minch, Ethiopia', in I Körner (ed.), *RAMIRAN 2015: 16th International Conference, Rural-Urban Symbiosis*, Hamburg, Germany, 8.-10. September, Hamburg University of Technology, pp. 645–8.

Yemaneh, A, Bulbo, M, Schmale, C & Otterpohl, R 2014, 'Investigation of Low-Cost Sugar Supplement for Lactic Acid Fermentation in Terra Preta Sanitation System', in T Bettendorf, C Wendland & Otterpohl (eds), *Terra Preta Sanitation*, 1st International Conference on Terra Preta Sanitation, Hamburg, Germany, 28-31 August 2013, Deutsche Bundesstiftung Umwelt, viewed 10 January 2018, <https://www.tuhh.de/t3resources/aww/publikationen/pdf/TPS-IC/20_A_Yemaneh_et_al.pdf>.

Yemaneh, A & Itchon, G 2015, 'Stabilization and hygienization of organic matter', in Deutsche Bundesstiftung Umwelt (ed.), *Terra Preta Sanitation: Backgrounds, principles and innovations*, Deutsche Bundesstiftung Umwelt, Osnabrück, Germany, pp. 120–33.

Literature Review on Water Efficiency in Agriculture: Sustainable Irrigation Methods

Maria Monina Orlina and Ruth Schaldach

'Adequate governance and knowledge levels are crucial for ensuring that water savings deliver their benefits of reducing pressure on water bodies, so that sustainable management of water quantities in all river basins of the EU can be achieved. Lastly, many solutions allow water saving in agriculture, but each solution must be adapted to the local situation. […] To find adapted solutions, the whole ecosystem must be considered, to account for all water needs, including environmental needs, and ensure they are met as adequately as possible.'

(BIO Intelligence Service 2012, p. 17)

Please cite as: Orlina, MM & Schaldach, R 2018, 'Literature Review on Water Efficiency in Agriculture: Sustainable Irrigation Methods' in R Schaldach & R Otterpohl (eds), RUVIVAL Publication Series, vol. 3, Hamburg, pp. 30 - 49, <http://nbn-resolving.de/urn:nbn:de:gbv:830-88218207>.

Abstract

Irrigation has been practiced worldwide for thousands of years. Irrigation systems and methods developed throughout history, but improvements are still needed, especially with regard to water efficiency. As water scarcity and the depletion of water resources increase, so do the water demands. The world population relies on irrigation for food production and therefore it is critical to reduce the pressure on freshwater bodies, while maintaining crop productivity. Irrigation management has varying effects on different stakeholders according to ample components affecting the irrigation management scheme, such as: soil type, climate, water availability, crop type and socio-economical influences in an area. One technique may be beneficial for short-term purposes, but cause negative consequences in the long run – this must be taken into consideration before implementation. There is no one way approach towards water efficiency. This paper will discuss the responses, methods, policies and proposed and practiced alternatives, as well as the corresponding difficulties and limitations, to increase water efficiency in agricultural irrigation.

Keywords: *sustainable irrigation, water efficiency, water research and innovation, literature review*

Introduction

Irrigated agriculture is one of the biggest water users in the world, with enormous regional variations. In Europe alone, an estimate of 40 billion m³ of water was used to irrigate approximately 10 million hectares of land in the year 2010 (EU 2016). Acquiring water supplies for irrigation has been a challenge and difficulty in many parts of the world where water is scarce and supplies are limited (Vaux 2012). Looking ahead, climate change will cause more severe droughts and intensify the pressure on water resources around the world (IEEP 2000). Climate change adaptation measures are already implemented in many parts of the world, however, these efforts need to be intensified.

Irrigation has received much criticism due to its environmental effects, such as damaged habitats and ecosystems, soil salinisation erosion and water pollution from pesticides, which are washed out during irrigation. As much as 60 % of abstracted water for irrigation does not reach crops and is wasted due to losses from evaporation, leakage, spillage, or infiltration (IEEP 2000). With rising global water challenges, much importance is given to water efficiency. This has become a legislative priority and has led to the adoption of several policies worldwide.

In the European Union (EU), policy instruments were established by the European Commission (EC) to promote water sustainability: the Water Framework Directive (WFD) (2000), which aims for the protection of available water resources and later also the 'Blueprint to Safeguard European Waters' (2012). Legislations are proposed for local implementation to improve water legislation throughout Europe (Poláková et al. 2013).

Water for irrigation relies mostly on surface and groundwater sources and the amount of water used depends on several factors, such as: climate, weather conditions, water quality, crop type, soil characteristics and irrigation techniques (EU 2016). To reduce the pressures on freshwater resources caused by irrigation, the BIO Intelligence Service (2012) suggests to:

1. Reduce water losses through technology and management,
2. Use alternative sources,
3. Comply with socio-economic measures.

Multiple actions and responses under these approaches are implemented or are on their way across the globe. However, in order to develop more technologies to improve water efficiency, research and scientific studies are needed. The results aid in information collection and sharing, as well as decision making (Poláková et al. 2013). On the European level, the European Innovation Partnerships on Water (EIP Water) and Agriculture (EIP Agriculture) were established to focus on research and innovation in promoting sustainable and efficient use of water (Poláková et al. 2013).

This paper discusses irrigation as a key activity for the survival of humans throughout history across the globe and presents common types of irrigation methods and systems. The relation between water and irrigation is described in more detail, including impacts on water inefficiencies caused by irrigation. Finally, the roles of policy, research, technology and management to improve water use efficiency in irrigation, as well as their difficulties and limitations, are discussed and reviewed.

Irrigation and Water

Approximately 1.2 billion people, who account for almost one fifth of the global population, live in areas where water is physically scarce, and another 1.6 billion deal with economic scarcity (UN Water 2005). With imminent urbanisation and effects of climate change, among other drivers, the demand for freshwater will increase and exacerbate water scarcity, especially in arid and semi-arid regions (Vaux 2012).

The agricultural sector is the largest user of water, accounting for 70 % of global freshwater usage, and more than 90 % in most of the least developed countries (WWAP 2014). Most of the volume of water goes to irrigation. Figure 1 illustrates areas equipped for irrigation in percentage of land area (Siebert et al. 2013).

To illustrate the relation between supply and demand of freshwater sources, the Millennium Development Goal (MDG) water indicator uses a ratio measuring the amount of human stress on water resources (see Figure 2, p. 33). The relation is between water withdrawal by agriculture, municipalities and industries over total renewable water resources (WWAP 2016).

The comparison of both maps illustrates, that most renewable resources suffer water stress in areas with irrigation in place.

According to estimations by United Nations World Water Assessment Programme (WWAP 2015), by the year 2050, there will be a need to produce 60 % more food in the whole world and 100 % more in developing countries, however, excessive blue water withdrawals for irrigation (Hoekstra et al. (2012) define blue water as fresh surface and groundwater, which include water in lakes, rivers and aquifers) can further intensify water scarcity and

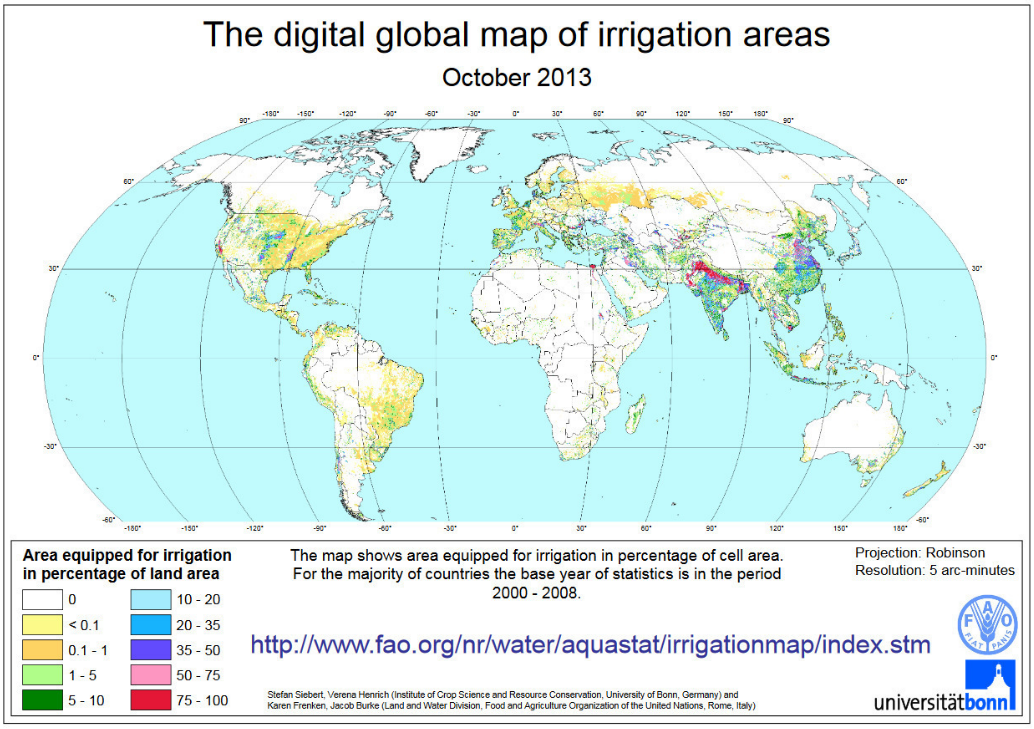

Figure 1 The Digital Global Map of Irrigation Areas (Siebert et al. 2013)

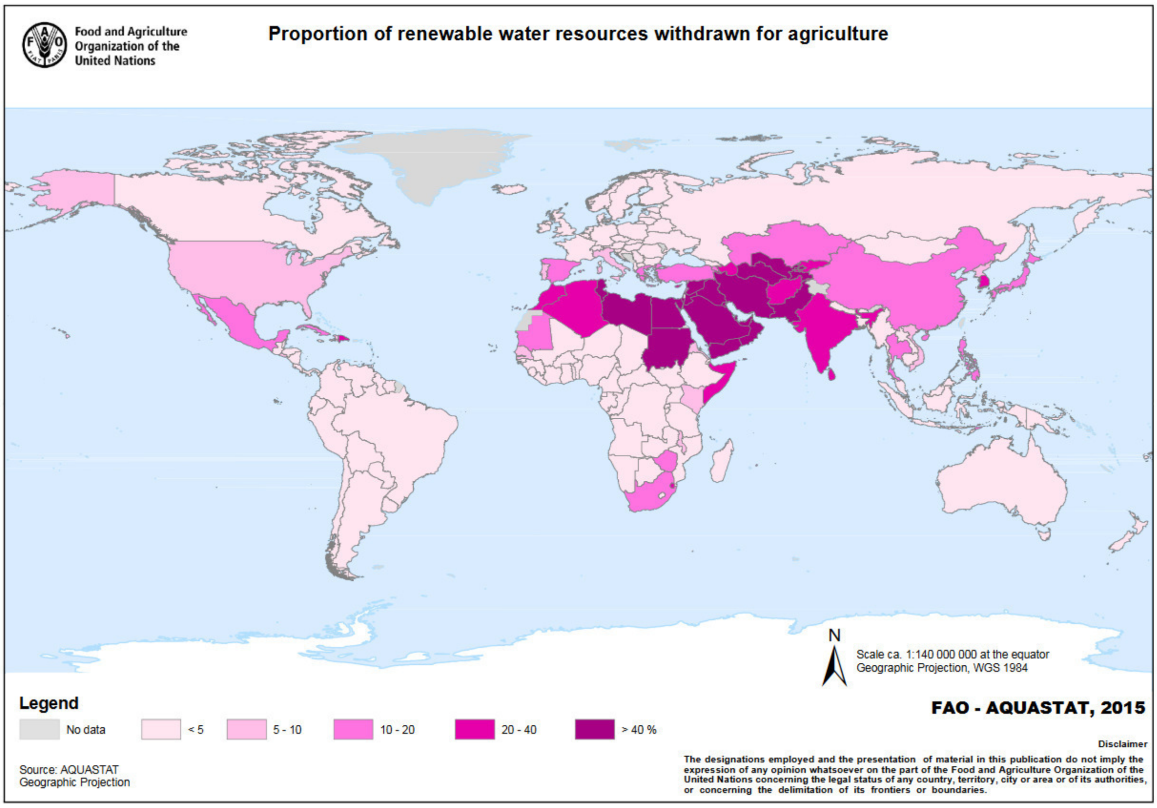

Figure 2 Percentage of Renewable Water Resources Withdrawn (FAO 2015a)

lead to various environmental problems. The global need to satisfy food demands and water conservation objectives are creating a paradox that will require a paradigm shift. This requires shifting the focus from maximising productivity per unit of land area to maximising productivity per unit of water consumed (Evans & Sadler 2008).

Aside from aggravating water scarcity, inefficient water use through irrigation has reduced river flows, destroyed habitats and ecosystems, and depleted aquifers (WWAP 2015). Another perplexing environmental impact is the land degradation. After irrigation, water evaporates from the soil. Irrigated water usually contains salt, which is left behind and accumulated in the soil. This is known as soil salinisation, a phenomenon which reduces soil productivity. Further, it can kill crops and lead to degraded and barren land (Ghassemi, Jakeman & Nix 1991). The common sources of irrigation salinity are over-irrigation, poor drainage and inefficient water use (State of New South Wales and Office of Environment and Heritage 2017). This can be addressed with proper drainage and improved irrigation systems.

As mentioned earlier, water in irrigation is sourced from either groundwater aquifers or surface water bodies (e.g. rivers, lakes and springs). With over-abstraction, when water abstraction exceeds natural recharge, the rapid decrease in the amount of water may affect: the physical and chemical characteristics of these water bodies and their interconnected biodiversity habitats (IEEP 2000). As for groundwater over-abstraction, aquifer water tables get lower and, consequently, flows into wetlands and rivers decrease (IEEP 2000). Another inefficiency in irrigation is that much of this water is wasted through leakage, spillage, infiltration and unproductive evaporation (FAO 1996). Specifically, inefficient infrastructure has become an issue diminishing water supply and losing as much as 50 % of abstracted water from leakages (Poláková et al. 2013).

In order to reduce the pressure by irrigation on water bodies, there are several approaches and options for irrigated agriculture to increase its water use efficiency. According to Evans & Sadler (2008), water efficiency can be increased when the total amount of water used by crops, losses and other users are reduced. However, it must be noted that multiple stakeholders are involved in decision-making processes and each have their own knowledge on irrigation. Farmers often assume that their irrigation practices are already adequately efficient and have no incentive to adopt innovative or more water efficient methods. Additionally, farmers aim to maximise productivity to gain the most profit, while the government, water experts and advocates aim to conserve water (Knox, Kay & Weatherhead 2012). Therefore, continuous knowledge exchange between stakeholders would be necessary to increase incentives to share responsibility for proper water management in irrigated agriculture. Moreover, these exchanges could construct practices that could benefit both the environment and the farmers (Levidow et al. 2014).

Irrigation in Agriculture

Irrigation is the practice of applying water, additional to what is provided by rainfall, to soil to allow plant growth and yield (Sojka, Bjorneberg & Entry 2002). This agricultural practice is believed to have begun around 6000 BCE in both Egypt and Jordan, where the first archaeological evidence of irrigation was found (Hillel 1994). A thousand years later, irrigation had spread to the Middle East and towards the Mediterranean. Simultaneously, it had independently begun across Asia, particularly in India and China (Reisner 1986). Towards the 19th century, irrigation principles were adapted based on developments in chemistry, mineralogy and biology. This gave birth to subdisciplines, such as agronomy and soil chemistry (Sojka, Bjorneberg & Entry 2002). The past century has seen even more advanced innovation in agricultural research and irrigation technologies. With growing food demands of an increased and consumerised world population (from 2.5 billion in 1950, to 7.5 billion 2015) the irrigated area doubled and water withdrawals tripled (FAO 2015b). Irrigated agriculture has helped to provide food supplies for growing demands, however, much improvement is needed in order to achieve sustainability and productivity at the same time, therefore, to address the environmental problems of today and tomorrow.

There are various irrigation methods being practiced today, each having their own advantages and disadvantages. The three commonly used methods are surface irrigation, sprinkler irrigation and drip irrigation.

Choosing an irrigation method is both an art and a science and experience proves the advantage of making a sound choice according to the applied environment. Several criteria need consideration, when selecting an irrigation method: soil type, climate, water availability, crop type, economics, social and cultural influences (Brouwer et al. 1990). The irrigation system should be designed to maximise productivity and minimise labour and capital. Farmers will implement those methods that are economically feasible and attractive. However, the irrigation system is also critical in achieving water efficiency and the following questions should be considered in irrigation system design: how much to apply, when to irrigate and how to improve efficiency? Each system has its own advantages and disadvantages, as stated above, but more often than not, there are additional unforeseen consequences and negative impacts that can arise from the implementation of these systems.

Surface Irrigation

Currently, surface irrigation is the most commonly used irrigation technique. It uses gravity to move water directly onto the field and can be divided into three categories: basin irrigation, furrow irrigation and border irrigation (Brouwer et al. 1990). This system is most appropriate for soil with good water holding capacity and internal drainage (Putnam 2012). The advantage of surface irrigation is that it does not involve the operation of sophisticated equipment, nor much capital investment, consequently mostly small farmers prefer this method. Additionally, surface irrigation does not require much energy and can be used for all types of crops. Surface irrigation can be efficient under certain conditions, as long as precise grading of topography and high level of management are present (Evans & Sadler 2008). However, compared to other irrigation systems, this traditional method tends to have high amounts of water losses through evaporation. Another disadvantage is that surface irrigation requires more labour in the construction, operation and maintenance. Other problems are waterlogging and soil salinisation (FAO 2002a).

Sprinkler Irrigation

Another commonly implemented irrigation type is the sprinkler irrigation, which is a method of applying water through a system of pipes and spraying it into the air through sprinklers, mimicking rainfall (Brouwer et al. 1990). The two most used sprinkler systems are centre pivot and linear systems. This type of irrigation can save water much better compared to surface irrigation systems, and can also be used where soil texture is light, such as sandy loams. The main advantage of sprinklers is their ability to distribute small amounts of water uniformly, reducing water wastage. Further, unlike surface irrigation, sprinklers require neither a till system nor land levelling. The main disadvantage of this type of irrigation is its higher capital investment and operating costs, compared to surface systems. These systems need pressure and, where there is no elevated reservoir, external energy to operate pumps. Another major disadvantage is the evaporative loss of water droplets, which can vary depending on weather and wind conditions of an area. Due to its high cost and capital investment per hectare, sprinkler irrigation is mostly used for high value cash crops, such as vegetables and fruit trees (Putnam 2012).

Drip Irrigation

Also known as trickle irrigation, drip irrigation is the application of water onto soil at very slow rates through pipes with outlets called drippers or emitters. Similar to sprinkler irrigation, this system is appropriate for areas with limited water and for sandy soils. An advantage of drip irrigation is that due to the dry surface, weeds are less likely to grow and farmers can even irrigate during harvest periods (Putnam 2012). Other advantages include minimising salinity hazards to plants, reducing labour through a simple automation system, and improving the soil-water regime for better crop yield (Bresler 1977). However, similar to sprinkler irrigation systems, major disadvantages are the high maintenance costs and great capital investment. Moreover, often operational difficulties occur due to clogging, accumulation of salt at the emitters and difficulty in system design due to external conditions and soil hydraulic properties. Drip irrigation has been promoted in several countries for its significant water saving potential, however the approach to push this technology without considering the scale and socioeconomic environment is criticised. A case study in Spain showed that drip irrigation may actually increase the total watershed water consumption, if agriculture would be made possible in areas where previously there was no agricultural land usage or if it would cause a crop shift (Sese-Minguez et al. 2017).

Subsurface Irrigation

Similar to drip irrigation, subsurface irrigation involves the application of water through pipes, but the tubes are about 12 cm below the surface. Unlike other types of irrigation, where water wets the entire soil, water is applied to a wetted area (Brouwer et al. 1990), removing any water losses from evaporation. A significant amount of water can be saved with this type of irrigation. Other advantages include less labour, reduced pumping energy and no soil or nutrient runoff. The tubes are also protected from UV (Ultraviolet radiation from sunlight) damage and are not easily hit by farming tools. Weed growth is reduced through a lack of surface water – however, after seeding, the flow has to be increased to reach the seeds. It is advisable to select systems of high quality as subsurface systems must be able to resist roots. The main disadvantage of this system is that problems are not visible immediately, as the pipes are below the ground, so maintenance, such as chemical injections and yearly clean-up flushing, is required (McDonald 2015).

Actions toward Water Efficiency

This chapter discusses the roles of policy, technology, management and research in obtaining water efficiency in irrigated agriculture. Several actions have been taken in order to save water and optimise water use in irrigation and ultimately reduce the pressure on surface and groundwater resources. Sustainable water use and efficiency through water resource management is needed to tackle the water crisis.

While most publications on irrigation are concerned with large scale farms, it should not be forgotten that globally most food (at least 70 %), especially in low-income and middle-income countries, is produced by small family farms (Altieri, Funes-Monzote & Petersen 2012; Herrero et al. 2017; Quan 2011) and that these can be much more productive per hectare/acre (Iheke & Nwaru 2013). This also translates to more 'crop per drop', especially if efficient irrigation is applied, too. Water demand can be reduced by intercropping, where higher plants provide shade for smaller ones (Narayanamoorthy, Devika & Bhattarai 2016; Ramulu 1998), reducing evaporation loss, and also the wasteful use of water by weeds is reduced. At the same time, root-mycorrhiza-systems of deep-rooting species can deliver water from deeper parts of the plot. Agroforests with water storage in thick roots, like Moringa trees (Debela & Tolera 2013; Sarwatt, Kapange & Kakengi 2002), can assure at least some production during the dry season without irrigation. It is also possible to make certain crops more water efficient by irrigating less, so that more and deeper roots will be developed (Buesa et al. 2017; Ford et al. 2017). Therefore, the irrigation system also needs to be implemented into a system of other water saving methods and combined with rainwater harvesting systems. These means of restoration farming can then turn farms into water producers providing irrigation water.

In order to reach a more integrated approach in managing water resources, proper policies and regulations must be in place to provide strategies for implementation. Social and economic aspects must be considered in drafting policies, or they will be difficult to implement. Sustainable water use policies focus on various sectors: agriculture, industry, energy and hygiene (WWAP 2015). This paper takes the EU as an example and focuses on the EU level. Actions towards water efficiency were established with the 'Roadmap to a Resource Efficient Europe' (2011), which defines goals for 2020 and 2050. By 2020, the impacts of droughts and floods should be minimised and abstraction of water should be below 20 % of available renewable water resources (EC 2011). By 2050, each person should have access to sufficient water supply with acceptable quality to sustain their lives, and a 'water secure world' should have been achieved. Specifically, agriculture would be more resilient towards precipitation variability with the practice of efficient irrigation techniques (WWAP 2015).

The previously mentioned WFD (Directive 2000/60/EC), adopted in 2000, is a policy instrument that requires to 'promote sustainable water use based on the long-term protection of available water resources' (EU 2016, p. 5). The Directive drafted the River Basin Management Plans (RBMP), with the main focus on integrated river basin management, a holistic approach in protecting the entire river basin and its parts. In (2012), the 'Blueprint to Safeguard European Waters' was published. The Blueprint's objective is to achieve sustainability for water-involved activities by proposing actions to improve water legislation and providing concrete solutions for implementation. The Food and Agriculture Organization of the United Nations (FAO) has a water scarcity program and it applies principles of Integrated Water Resource Management (IWRM) for the agriculture sector, centred on water efficiency and conservation (FAO 2014). However, all these policies would be useless without good governance and proper enforcement of regulations.

Water use efficiency reduces the pressure on water resources in several ways, called 'responses' (BIO Intelligence Service 2012), such as using alternative sources of water, monitoring water use or recycling water. In the BIO Intelligence Service study (2012), these responses were categorised under three approaches: technological and management approaches, use of other water sources and socio-economic responses.

Technological and Managerial Approaches

The first category, technological and management approaches, aims to save water by decreasing water losses. Water is lost in irrigation during several steps throughout the process.

To address these, the BIO Intelligence Service (2012) investigated these responses:

1. Improvement of irrigation systems,
2. Deficit irrigation strategies,
3. Reduction of evaporation during storage,
4. Decreasing soil evaporation,
5. Irrigation scheduling,
6. Reducing runoff,
7. Water table management,
8. Changing planting date,
9. Crop selection.

In the study of BIO Intelligence Service (2012), water losses were identified and connected to strategies considering location and specific actions to reduce these losses. Figure 3 shows a schematic of blue water use in irrigation.

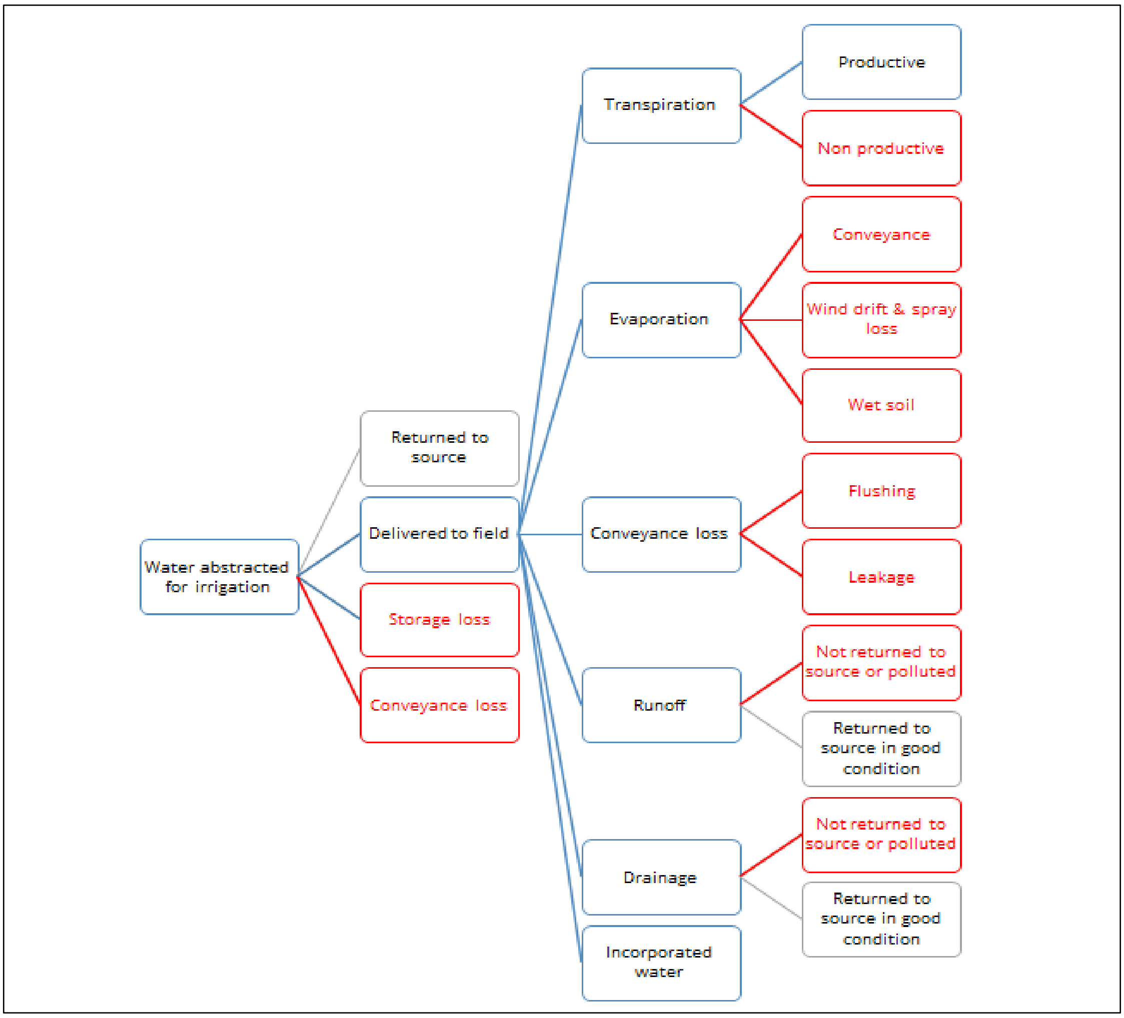

Figure 3 Scheme of Water Use and Water Losses, adapted from BIO Intelligence Service (2012, p. 43)

Non-productive water losses, storage loss, conveyance loss, leakage, flushing, etc., are marked in red. Grey boxes depict water which is returned to the source in good condition.

Some responses, which can help minimise or avoid these losses, will be discussed in more detail in the following chapters.

Improvement of the Irrigation System

The three main types of irrigation systems are: surface, sprinkler and drip irrigation, each have their own advantages and disadvantages, as mentioned previously (see p. 35). The amount of water to cultivate the land is dependent on the type of system chosen and can greatly impact the basin from which water is abstracted. Drip irrigation is found in some studies to be the most water efficient system as it applies water to areas needed by the crop, wasting little to none (FAO 2002a), resulting in numerous governments worldwide promoting its adoption. Based on the United States Statistic Services, drip irrigation can achieve the efficiency of up to 95 %, when implemented with effective monitoring, proper design systems and management (Evans & Sadler 2008). In the United States, it is currently used in approximately 5 % of the irrigated land (USDA & NASS 2002).

However, there has been recent debate and criticism questioning whether shifting from traditional irrigation practices to drip irrigation is actually more water efficient. Several studies have investigated unforeseen effects on water and energy consumption in the long run. These recent works have focused on the rebound effect, explaining that adoption of a new technology aimed to increase the efficiency of a resource does not necessarily lead to less consumption (Sanchis-Ibor et al. 2015). Previously, studies were conducted using just analytical or mathematical models to investigate the effects of drip irrigation in water saving, but only recent studies analyse the implementation of drip irrigation ex post (Narayanamoorthy 2004; Sanchis-Ibor et al. 2015). One of the most notable case studies is in Spain, whose irrigation modernisation programme, under the Horizon 2008 National Irrigation Plan (MAPAMA 2002), is possibly the largest in terms of surface area and investment in the whole of Europe and one of the largest programmes in the world (Lopez-Gunn, Mayor & Dumont 2012; Sanchis-Ibor et al. 2015; Sese-Minguez et al. 2017).

Within the National Irrigation Modernisation Programme, an investigation was conducted on the Canyoles watershed in Valencia (Sese-Minguez et al. 2017) to assess the consequences and impacts due to the shift from surface irrigation to drip irrigation during the past 25 years, and to highlight the significance of different stakeholders involved in irrigation. One of the most evident effects was that with the modernisation of irrigation, the amount of water and irrigated land increased (Lopez-Gunn, Mayor & Dumont 2012; Sese-Minguez et al. 2017). Drip irrigation actually led to the opening of more wells, allowing farmers to abstract groundwater. Additionally, there was an expansion in total irrigated land due to the technology advancement. These two effects actually contradict the whole purpose of adopting drip irrigation, which was to increase water savings (Sese-Minguez et al. 2017). Another consequence, reported in this study, was the increase of energy use. Drip irrigation requires power to operate effectively, in contrast to surface irrigation, which uses mostly gravity to work. Electrical pumps are used to lift the groundwater, resulting in high energy consumption (Sese-Minguez et al. 2017). In a similar study done also in Valencia by Ibor, Molla & Reus (2016), it was discovered in interviews that increases in energy costs are hindering farmers from adopting the drip irrigation system. Ibor, Molla & Reus (2016) discuss that policies and actions aimed to promote water efficient technologies should properly assess the projected reduction in water consumption, and increase in energy consumption. Further, they should evaluate the impacts on costs for farmers' finances, as well as the effects on heritage conservation (Ibor, Molla & Reus 2016, p. 503). In another report by van der Kooij et al. (2013), they conclude that improved water efficiency from drip irrigation will only be achieved under very defined operational conditions and specific spatial and temporal circumstances. Further, Evans & Sadler (2008) report that improving on-farm irrigation systems may not reduce water for the whole hydrological system, i.e. the river basin, raising some confusion. Therefore, researchers are imploring to policy makers to not base their findings on studies that report efficiency gains achieved at farm levels, which do not accurately reflect the implications on larger scales.

Deficit Irrigation

Deficit irrigation involves the application of less water than the crop's requirement. This can be achieved by either decreasing the amount of water irrigated during certain growth stages or by a technique called partial root zone drying. This modern technique requires irrigating one part of the root zone while leaving the other part dry, before wetting the dry part later on (BIO Intelligence Service 2012). Deficit irrigation has been applied to various crops in countries around the world, but this technique involves significant crop and soil knowledge and accurate water control and management. Recently, major improvements have been developed with advanced technologies, such as soil water sensors, which aid farmers to manage their resources and strategise irrigation scheduling (FAO 2002b). As an example, deficit irrigation practiced in Australia with fruit trees has resulted in around 60 % increase of water productivity and gain in fruit quality, without yield loss (WWAP 2015).

Irrigation Scheduling

Decision support tools, such as irrigation scheduling, can reduce water losses by maximising irrigation efficiency and optimising the water used on crops in terms of timing and amount. Scheduling can be applied to most crops and to every basin, as long as information on weather, hydrological flow and soil are available (BIO Intelligence Service 2012). Farmers can receive training to monitor parameters in order to create their own irrigation schedules. Irrigation scheduling services, in form of information bulletins, training courses, among others, are provided in several EU countries. In France, agricultural agencies collect field data and publish irrigation bulletins via newsletters and training courses (Meteo France 2018). Similarly, in Greece, irrigation scheduling services are provided through fax and telephone (Hellenic Ministry of Rural Development and Food 2018). There are also web-based platforms, which give information based on weather data and models to assist with water management and irrigation scheduling. Examples of these online systems are CROPWAT, WaterBee, WaterWatch and IRRINET (Poláková et al. 2013). Such systems assisted in reducing as much as 20 % of annual water usage in the Po River (Poláková et al. 2013).

Crop Selection

Each crop has its own daily and seasonal water need. Using crops which need less irrigation water or that better tolerate drought is another way to save irrigated water. There are certain crops that have the ability to uptake water from deeper soil layers. To give an example, sorghum and sunflower are drought tolerant crops, which both have efficient root systems and can adapt to different water availabilities (BIO Intelligence Service 2012). Today, around 20 million tons of cotton, one of the most water intense crops, is produced every year globally, even in water scarce areas. An astonishing 20,000 L of water is needed to produce just 1 kg of cotton (WWF 2017a). Moreover, the massive production of biofuel crops, such as corn and sugar, has created additional stress on water supplies and can cause greater water depletion with the acceleration of biofuel production in future years (National Research Council 2008). Another example is the production of dry rice. Flood irrigation (surface irrigation) is the traditional way of farming rice and requires at least 3 to 5 thousand litres of water to produce one kilogram. Shifting to the System of Rice Intensification (SRI), much more rice can be produced with the same amount of water. A study in India shows an increase in crop yield and with almost 30 % less water usage with this system (WWF 2017b). Stronger agricultural policies covering these issues must be in place. Further, farmers need to be trained and educated regarding crop selection and should also be given incentives to use water efficient crops (BIO Intelligence Service 2012).

Improve Water Holding Capacity of Soil

The water holding capacity of soil is an important characteristic because soils that hold more water can support more plant growth (Agvise Laboratories 2017). Knowing this capacity helps optimise crop production and the main components to determine this are soil texture and organic matter. Organic matter or compost is essential for the life and function of soil, as it increases the soil's magnetism and absorption of water (Yang et al. 2017). Further organic matter also influences soil structure and benefits the diversity of soil organisms (FAO 2005). Reports have found that that for every 1 % of organic matter content, the soil can hold 16,500 gallons of plant-available water per acre of soil (Gould 2015). Finally it was stated that water used for irrigation may be reduced with the efficient water use characteristics of compost, creating drought resistant soil (Gould 2015). Increasing the organic matter can be done by adding plant or animal material to the soil.

Using Water from Other Sources

The second approach, 'Use of other Water Sources', does not exactly save water, but does reduce the pressure on water bodies by reducing abstraction from ground and surface water and providing water for certain areas during times of drought or scarce water supply (BIO Intelligence Service 2012). The three responses under this category are: Water Reuse, On-farm Storage and Water Harvesting.

Water reuse or wastewater recycling is an option to irrigate green areas and some types of crops, and may even have nutrients beneficial to certain plants. Further, water reuse decreases the need and therefore also cost of fertiliser and can also recharge aquifers with treated water through infiltration, thus reducing the water treatment costs (Jiménez 2006). This technique is currently practiced in several countries, such as Spain, where approximately 76 % of reused wastewater is allocated to irrigated agriculture (AQUAREC 2006). Though water reuse is a way to reduce pressure on freshwater resources, the use of wastewater is a major sanitation and safety issue, creating an obstacle for it to be adapted as an alternative for farmers in countries where environmental and health standards have not yet been established.

Furthermore, there are two methods how water can be collected and stored in order to be used when supply is limited. The first is 'On-Farm Storage', wherein water is abstracted from surface or groundwater during times of abundant supply. Technically, water is not saved and could even lead to water losses through evaporation and seepage during storage, and, therefore, this method is not recommended. The second method is through Rain Water Harvesting, wherein water from rainfall is collected. Similarly, this does not necessarily save water, but it transfers to usage of water from blue water (surface and groundwater) to green water (rainwater). This method too has its side effects – harvesting rainwater impacts the water balance in the basin, and these effects must be given attention as well (BIO Intelligence Service 2012).

Socio-Economic Responses

The third category, Socio-Economic Responses, seeks to change and improve the way farmers manage their resources by raising awareness (or through regulations) and giving incentives (through water pricing and trainings). Through these responses, water is saved directly by encouraging water efficient approaches and the use of modern technologies, and by enforcing the implementation of better water resource management (BIO Intelligence Service 2012).

Water monitoring aims to quantify the volume of water abstracted from surface and groundwater used for irrigation. Auditing aids help farm owners to compute their water footprint and identify water losses and inefficiencies in their irrigation systems. Major advancements, such as remote sensing and GIS technologies, have significantly helped to measure and monitor water. These tools do not directly save water, but they allow for the assessment of water needs by collecting information that could ultimately improve water efficiency (i.e. help farmers with the irrigation schedules) (Poláková et al. 2013). Moreover, Satellite mapping and Global Monitoring for Environment and Security programme (GMES/COPERNICUS), which are technological developments in water monitoring, locate illegal abstractions and allow governments to properly control water resources (EU 2012).

Water regulations aim to inform farmers and water users of scarcity issues and give them incentives to reduce their water use (BIO Intelligence Service 2012). In Portugal, regulations require farmers to report water losses, travel time of water and dates of irrigation, allowing them to schedule and organise their water use. Furthermore, the allocation of 'water rights' controls water abstraction amounts and encourages farmers to improve their irrigation and distributions systems, i.e. convert to drip irrigation (Dworak, Berglund & Laaser 2007). Water allocation is managed through water permits, which distribute the water among all sectors and users: industry, agriculture, municipal needs, etc. In terms of irrigation, water pricing is used as an economic tool to allocate water for crops that generate the highest value economically (BIO Intelligence Service 2012). However, there is much controversy regarding the setting of a tariff on water. Sometimes setting tariffs takes place for political rather than practical purposes, where free water is used as a campaign promise to gain votes (Ricato n.d.). Further, there is a disagreement on the 'right' way to price water. A debate arises over the objectives of water pricing conflict with the needs of consumers and other stakeholders. Consumers want affordable and fair water services, while the utilities need stable revenues for operations and profit. There is a difficulty for a tariff structure to find the balance to satisfy both sides. First of all, people do not know the cost of providing water, making it difficult to agree on a fair price. Secondly, there is a lack of data to show what would happen if a certain tariff was implemented and how consumers would behave to these prices. Finally, there is no existing market test for these structures, thus prices are usually set by regulatory agencies without the participation of the private sector or consumers. All these factors play into the difficulty of reaching a consensus over water pricing (Whittington 2006).

EIP Water, proposed by the Europe 2020 Flagship (EC n.d.), is aimed to be a catalyst for research and innovation in finding solutions to water challenges, and to create jobs for economic growth in the water sector. To achieve this goal, integration is required among several disciplines: research, information and communication technologies, governance and financing, among others (EU 2013b). EIP Water seeks to promote efficient water use by identifying barriers to innovation and finding ways to eliminate them. Furthermore, water innovation will be accelerated through interactions between research, water users, technology development and legislative requirements. EIP Water serves as a key tool in supporting the policy options identified in the 'Blueprint to Safeguard Europe's Water Resources' (EU 2013a).

Conclusion

Irrigation has been critical in providing food to a majority of the Earth's population throughout history and will be needed to supply future food demands. Despite its consequential problems and challenges, there is a trade-off between water conservation and the need to feed the population of the world. This created a paradigm shift towards maximising productivity per unit of water consumed. It is evident and imperative that water will be more efficiently used in agricultural irrigation and growing water intensive cash crops like cotton in water stressed areas is not a wise – but very common practice. Negative impacts of over-abstraction have affected water tables, soil quality, and biodiversity. Water loss through irrigation is a major issue that requires immediate attention and reducing losses would be a great contribution to water saving. Despite multiple problems faced today in regard to water – scarcity, soil destruction, drought and climate change – there is still hope to improve water efficiency.

Through the canon of approaches: technological advancements, management improvements, policy regulations, and continued research and innovation, solutions can be found to reduce the pressure on our limited blue water resources – surface and groundwater. Responses include use of other water sources and socio-economic responses, such as water monitoring and auditing. However, all these changes will require a systematic approach, taking into consideration several factors and components before implementation. These include the positive and negative implications to all stakeholders, the relevance of these actions to local soil and crop conditions, and the impacts on the river basins and their habitats. Recent research and investigations have questioned the validity of water conservation policies promoting 'water efficient' technologies, such as drip irrigation, which have actually resulted in unforeseen consequences, i.e. increase water use through the expansion of more irrigated land. Most of these policies were made based on mathematical models and projections. Therefore, changes in policy structures are necessary, based continued research, ex post analysis, and complete assessments on how appropriate and effective an improvement would be in a larger scale. Despite the challenges presented, there is great potential for irrigated agriculture to reduce its water consumption while maintain productivity in order to satisfy food needs and requirements, however one of the first measures should be to improve the water holding capacity of soil and to make irrigation by choosing the right crops less necessary.

Picture Credits

Figure 1 (p. 32) The Digital Global Map of Irrigation Areas
Source: Siebert et al. (2013) – content may be copied, printed and downloaded for private study, research and teaching purposes, and for use in non-commercial products or services, provided that appropriate acknowledgement of FAO as the source and copyright holder is given and that FAO's endorsement of users' views, products or services is not stated or implied in any way.

Figure 2 (p. 33) Percentage of Renewable Water Resources Withdrawn
Source: FAO (2015a) – content may be copied, printed and downloaded for private study, research and teaching purposes, and for use in non-commercial products or services, provided that appropriate acknowledgement of FAO as the source and copyright holder is given and that FAO's endorsement of users' views, products or services is not stated or implied in any way.

Figure 3 (p. 38) Scheme of Water Use and Water Losses
Adapted from BIO Intelligence Service (2012, p. 43)

References

Agvise Laboratories 2017, *Water holding capacity*, Agvise Laboratories, viewed 13 March 2017, <http://www.agvise.com/educational-articles/water-holding-capacity/>.

Altieri, MA, Funes-Monzote, FR & Petersen, P 2012, 'Agroecologically efficient agricultural systems for smallholder farmers: Contributions to food sovereignty', *Agronomy for Sustainable Development*, vol. 32, no. 1, pp. 1–13.

AQUAREC 2006, *Integrated concept for reuse of upgraded wastewater: Report on integrated water reuse concepts*, T Wintgens & R Hochstrat, viewed 22 February 2017, <http://www.susana.org/_resources/documents/default/2-551-wintgens-hochstrat-2006-d19-integrated-reuse-aquarec-en.pdf>.

BIO Intelligence Service 2012, *Water saving potential in agriculture in Europe: Findings from the existing studies and application to case studies*, Final report prepared for European Commission DG ENV, Paris, viewed 13 March 2017, <http://ec.europa.eu/environment/water/quantity/pdf/BIO_Water%20savings%20in%20agiculture_Final%20report.pdf>.

Bresler, E 1977, 'Trickle-Drip Irrigation: Principles and Application to Soil-Water Management', in Brady (ed.), *Advances in Agronomy*, Academic Press, pp. 343–93.

Brouwer, C, Prins, K, Kay, M & Heibloem, M 1990, *Irrigation water management: irrigation methods: Training Manual No. 5: Irrigation methods*, Food and Agriculture Organization of the United Nations, Rome, Italy, viewed 16 February 2017, <ftp://ftp.fao.org/agl/aglw/fwm/Manual5.pdf>.

Buesa, I, Pérez, D, Castel, J, Intrigliolo, DS & Castel, JR 2017, 'Effect of deficit irrigation on vine performance and grape composition of Vitis vinifera L. cv. Muscat of Alexandria', *Australian Journal of Grape and Wine Research*, vol. 23, no. 2, pp. 251–9.

Debela, E & Tolera, A 2013, 'Nutritive value of botanical fractions of Moringa oleifera and Moringa stenopetala grown in the mid-Rift Valley of southern Ethiopia', *Agroforestry Systems*, vol. 87, no. 5, pp. 1147–55.

Dworak, T, Berglund, M & Laaser, C 2007, *EU water saving potential: Part 1 – Report*, Ecologic - Institute for International and European Environmental Policy, Berlin, Germany, viewed 27 February 2017, <http://ecologic.eu/sites/files/project/2013/917_water_saving_1.pdf>.

EC n.d., *Europe 2020 strategy*, viewed 26 January 2018, <https://ec.europa.eu/info/business-economy-euro/economic-and-fiscal-policy-coordination/eu-economic-governance-monitoring-prevention-correction/european-semester/framework/europe-2020-strategy_en>.

Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy 2000 (EC), viewed 16 November 2017, <http://eur-lex.europa.eu/eli/dir/2000/60/oj>.

——2011, *Roadmap to a resource efficient Europe: COM/2011/0571 final*, Brussels, viewed 17 February 2017, <http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52011DC0571&from=EN>.

EU 2012, *A Blueprint to Safeguard Europe's Water Resources: COM/2012/0673 final*, 2012, viewed 26 January 2018, <http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52012DC0673>.

——2013a, *EIP Water: About EIP water - Basics*, European Innovation Partnership on Water & European Union, viewed 27 February 2017, <http://www.eip-water.eu/about/basics>.

——2013b, *EIP Water: About EIP water - Basics - Opportunities for water innovation*, 27 February, European Innovation Partnership on Water & European Union, viewed 27 February 2017,

<http://www.eip-water.eu/basics/opportunities-water-innovation>.

——2016, *Statistics Explained: Agri-environmental indicator - irrigation*, 24 March, Eurostat & European Union, Luxembourg, viewed 16 February 2017, <http://ec.europa.eu/eurostat/statistics-explained/index.php/Agri-environmental_indicator_-_irrigation>.

Evans, RG & Sadler, EJ 2008, 'Methods and technologies to improve efficiency of water use', *Water Resources Research*, vol. 44, no. 7.

FAO 1996, *Special Programme for Food Security: Poor irrigation management: a threat to soil, water and food security*, 16 September, Food and Agriculture Organization of the United Nations, viewed 17 February 2017, <http://www.fao.org/focus/e/speclpr/spro13-e.htm>.

——2002a, *Crops and drops: Making the best use of water for agriculture*, Food and Agriculture Organization of the United Nations, Rome, Italy, viewed 17 February 2017, <http://www.fao.org/docrep/005/y3918e/y3918e10.htm>.

——2002b, *Deficit irrigation practices*, Water reports, vol. 22, Food and Agriculture Organization of the United Nations, Rome, Italy, viewed 17 February 2017, <http://www.fao.org/docrep/004/Y3655E/y3655e00.htm>.

——2005, *The importance of soil organic matter: Key to drought-resistant soil and sustained food production*, FAO Soil Bulletin, vol. 80, Rome, Italy, viewed 13 March 2017, <http://www.fao.org/docrep/009/a0100e/a0100e08.htm>.

——2014, *Building a common vision for sustainable food and agriculture: Principles and approaches*, Food and Agriculture Organization of the United Nations, Rome, Italy, viewed 17 February 2017, <http://www.fao.org/3/a-i3940e.pdf>.

——2015a, *Proportion of renewable water resources withdrawn for agriculture*, AQUASTAT website, Food and agriculture organization of the United Nations, <http://www.fao.org/nr/water/aquastat/maps/WithA.TRWR_eng.pdf>.

——2015b, *Water development and management unit: irrigation*, 6 October, Food and Agriculture Organization of the United Nations, viewed 17 February 2017, <http://www.fao.org/nr/water/topics_irrigation.html>.

Ford, T, Hartman, C, Nagchaudhuri, A, Mitra, M & Marsh, L 2017, 'Analysis of Yield Response with Deficit Drip Irrigation Strategies, Remote Sensing with UAVs, and Thermal Image Processing', *ASABE Annual International Meeting*, Spokane, United States, 16-19 July, ASABE.

Ghassemi, F, Jakeman, AJ & Nix, HA 1991, 'Human induced salinisation and the use of quantitative methods', *Environment International*, vol. 17, no. 6, pp. 581–94.

Gould, MC 2015, *Compost increases the water holding capacity of droughty soils*, 16 October, Michigan State University, viewed 13 March 2017, <http://msue.anr.msu.edu/news/compost_increases_the_water_holding_capacity_of_droughty_soils>.

Hellenic Ministry of Rural Development and Food 2018, *Farmers Call Center*, viewed 29 January 2018, <http://www.minagric.gr/index.php/en/>.

Herrero, M, Thornton, PK, Power, B, Bogard, JR, Remans, R, Fritz, S, Gerber, JS, Nelson, G, See, L, Waha, K, Watson, RA, West, PC, Samberg, LH, van de Steeg, J, Stephenson, E, van Wijk, M & Havlík, P 2017, 'Farming and the geography of nutrient production for human use: A transdisciplinary analysis', *The Lancet Planetary Health*, vol. 1, no. 1, e33-e42.

Hillel, D 1994, *Rivers of Eden: The struggle for water and the quest for peace in the Middle East*, Oxford University Press, New York.

Hoekstra, AY, Chapagain, AK, Aldaya, MM & Mekonnen, MM 2012, *The Water Footprint Assessment Manual: Setting the Global Standard*, Earthscan, London, United Kingdom, viewed 20 April 2017, <http://waterfootprint.org/en/water-footprint/glossary/#BW>.

Ibor, CS, Molla, MG & Reus, LA 2016, 'Drip irrigation implementation policies. effects on the water users' associations of the Valencia region', *Boletín de la Asociación de Geógrafos Españoles*, no. 72, pp. 503–6.

IEEP 2000, *The environmental impacts of irrigation in the European Union*, Insitute of European Environmental Policy, London, Polytechnical University of Madrid & University of Athens, viewed 16 February 2017, <http://ec.europa.eu/environment/agriculture/pdf/irrigation.pdf>.

Iheke, OR & Nwaru, JC 2013, 'Innovation Adoption, Farm Productivity and Poverty Status of Rural Smallholder Farm Households in South-East, Nigeria', in AAAE (ed.), *Commercializing Agriculture in Africa: Social, Economic and Environmental Impacts*, 4th African Association of Agricultural Economists conference, Hammamet, Tunisia, 22-25 September, African Association of Agricultural Economist, Nairobi, Kenya, <http://ageconsearch.umn.edu/record/161627/files/Onwuchekwa%20Raphael%20Iheke%20and%20Jude%20Chukwudi%20Nwaru.pdf>.

Jiménez, B 2006, 'Irrigation in Developing Countries Using Wastewater', *International Review for Environmental Strategies*, vol. 6, no. 2, pp. 229–50.

Knox, JW, Kay, MG & Weatherhead, EK 2012, 'Water regulation, crop production, and agricultural water management: Understanding farmer perspectives on irrigation efficiency', *Agricultural Water Management*, vol. 108, pp. 3–8.

Levidow, L, Zaccaria, D, Maia, R, Vivas, E, Todorovic, M & Scardigno, A 2014, 'Improving water-efficient irrigation: Prospects and difficulties of innovative practices', *Agricultural Water Management*, vol. 146, pp. 84–94.

Lopez-Gunn, E, Mayor, B & Dumont, A 2012, 'Implications of the modernization of irrigation systems', in L de Stefano & MR Llamas (eds), *Water, Agriculture and the Environment in Spain: Can we square the circle?*, CRC Press, Boca Raton, Florida, pp. 241–56.

MAPAMA 2002, *Plan Nacional de Regadios* (Spanish), Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente, viewed 29 January 2018, <http://www.mapama.gob.es/en/desarrollo-rural/temas/gestion-sostenible-regadios/plan-nacional-regadios/texto-completo/>.

McDonald, K 2015, *Big Picture Agriculture: Thirty-five water conservation methods for agriculture, farming, and gardening Part 1*, Weblog, Colorado, United States, viewed 28 May 2017, <https://bigpictureagriculture.blogspot.de/2015_10_20_archive.html>.

Meteo France 2018, *Données publiques* (French), viewed 29 January 2018, <https://donneespubliques.meteofrance.fr/?fond=caracteristique&caracteristique=11&caracdisp=28>.

Narayanamoorthy, A 2004, 'Impact Assessment of Drip Irrigation in India: The Case of Sugarcane', *Development Policy Review*, vol. 22, no. 4, pp. 443–62.

Narayanamoorthy, A, Devika, N & Bhattarai, M 2016, 'More Crop and Profit per Drop of Water: Drip Irrigation for Empowering Distressed Small Farmers', *IIM Kozhikode Society & Management Review*, vol. 5, no. 1, pp. 83–90.

National Research Council 2008, *Water Implications of Biofuels Production in the United States*, The National Academies Press, Washington, D.C.

Poláková, J, Farmer, A, Berman, S, Naumann, S, Frelih-Larsen, A & van Toggenburg, J von 2013, *Sustainable management of natural resources with a focus on water and agriculture*, Brussels, viewed 16 February 2017, <http://www.europarl.europa.eu/stoa/webdav/site/cms/shared/2_events/workshops/2013/20131016/STOA%20Final%20Report%20Nat%20%20Res%20%20May%202013%20v2.pdf>.

Putnam, D 2012, 'Strategies for the improvement of water-use efficient irrigated alfalfa systems', in D Putnam (ed.), *42nd California Alfalfa & Grains Symposium*, Sacramento, California, 10-12 December, University of California Cooperative Extension, Department of Plant Sciences, viewed 1 March 2017, <http://alfalfa.ucdavis.edu/+symposium/2012f/files/talks/12CAS-2%20_Putnam_IrrigationStrategies.pdf>.

Quan, J 2011, *A future for small-scale farming: Science review: SR25*, Foresight Project on Global Food and Farming Futures, London, United Kingdom, viewed 8 November 2017, <https://www.nri.org/images/documents/news2011/11-570-sr25-future-for-small-scale-farming.pdf>.

Ramulu, S 1998, *Management of water resources in agriculture*, New Age International, New Delhi, India.

Reisner, M 1986, *Cadillac desert: The American West and its disappearing water*, Penguin Books, New York, United States.

Ricato, M n.d., *Water Pricing*, Sustainable Sanitation and Water Management, viewed 29 January 2018, <https://www.sswm.info/category/planning-process-tools/implementation/implementation-support-tools/financing/water-pricing->.

Sanchis-Ibor, C, Macian-Sorribes, H, Garcia-Molla, M & Pulido-Velazquez, M 2015, 'Effects of drip irrigation on water consumption at basin scale (Mijares river, Spain)', in ICID (ed.), *Innovate to improve irrigation performance*, 26th Euro-mediterranean Regional Conference and Workshops, Montpellier, France, 11-16 October, International Comission on Irrigation and Drainage, viewed 2 March 2017, <https://icid2015.sciencesconf.org/75019/document>.

Sarwatt, SV, Kapange, SS & Kakengi, AMV 2002, 'Substituting sunflower seed-cake with Moringa oleifera leaves as a supplemental goat feed in Tanzania', *Agroforestry Systems*, vol. 56, no. 3, pp. 241–7.

Sese-Minguez, S, Boesveld, H, Asins-Velis, S, van der Kooij, S & Maroulis J. 2017, 'Transformations accompanying a shift from surface to drip irrigation in the Cànyoles Watershed, Valencia, Spain', *Water Alternatives*, vol. 10, no. 1, pp. 81–99.

Siebert, S, Henrich, V, Frenken, K & Burke, J 2013, *The Digital Global Map of Irrigation Areas*, AQUASTAT & Food and agriculture organization of the United Nations, viewed 20 April 2017, <http://www.fao.org/nr/water/aquastat/irrigationmap/gmia_v5_lowres.pdf>.

Sojka, RE, Bjorneberg, DL & Entry, JA 2002, 'Irrigation: an historical perspective', in R Lal (ed.), *Encyclopedia of soil science*, Marcel Dekker, New York, United States, pp. 745–9, viewed 16 February 2017, <https://eprints.nwisrl.ars.usda.gov/815/1/1070.pdf>.

State of New South Wales and Office of Environment and Heritage 2017, *Type of salinity and their prevention*, 25 July, Sydney, Australia, viewed 13 March 2017, <http://www.environment.nsw.gov.au/salinity/solutions/irrigation.htm>.

UN Water 2005, 'Coping with water scarcity: challenge of the twenty-first century', *Waterlines*, vol. 24, no. 1, pp. 28–9.

USDA & NASS 2002, *Census of Agriculture*, U.S. Department of Agriculture & National Agricultural Statistics Service, Washington, D.C., United States, viewed 20 April 2017, <https://www.nass.usda.gov/>.

van der Kooij, S, Zwarteveen, M, Boesveld, H & Kuper, M 2013, 'The efficiency of drip irrigation unpacked', *Agricultural Water Management*, vol. 123, pp. 103–10.

Vaux, H 2012, 'Water for agriculture and the environment: The ultimate trade-off', *Water Policy*, vol. 14, S1, pp. 136–46.

Whittington, D 2006, *Pricing water and sanitation services: Human Development Report 2006*, UNDP, viewed 2 March 2017, <http://hdr.undp.org/sites/default/files/whittington.pdf>.

WWAP 2014, *The United Nations world water development report 2014: Water and Energy*, vol. 1, United Nations World Water Assessment Programme, UNESCO, Paris.

——2015, *The United Nations world water development report 2015: Water for a Sustainable World*, United Nations World Water Assessment Programme, UNESCO, Paris.

——2016, *The United Nations world water development report 2016: Water and Jobs*, United Nations World Water Assessment Programme, UNESCO, Paris, viewed 20 April 2017, <http://unesdoc.unesco.org/images/0024/002439/243938e.pdf>.

WWF 2017a, *Cotton farming: Cotton: a water wasting crop*, World Wide Fund For Nature, viewed 21 March 2017, <http://wwf.panda.org/about_our_earth/about_freshwater/freshwater_problems/thirsty_crops/cotton/>.

——2017b, *Thirsty crops cause water shortages and pollution*, World Wide Fund For Nature, viewed 21 March 2017, <http://wwf.panda.org/about_our_earth/about_freshwater/freshwater_problems/thirsty_crops/>.

Yang, H, Xiong, H, Chen, X, Wang, Y & Zhang, F 2017, 'Identifying the influence of urbanization on soil organic matter content and pH from soil magnetic characteristics', *Journal of Arid Land*, vol. 7, no. 6, pp. 820–30.