Adaptations in Water Harvesting Technologies for Enhancing Food Security and Livelihood: A Multi-country Study in Sub-Saharan Africa

D. Snelder, F. Kahimba, O. Korodjouma, A. Abebe, E. Oughton, L. Bunclark and R. Lasage

Abstract The objective of this paper was to examine farmer-directed technology adaptation of selected water harvesting technologies (WHTs) in order to enhance their potential contribution to food security and livelihood improvement in sub-Saharan Africa. The selected WHTs included micro- and meso-scale reservoirs that store water in the soil (in situ) or in a reservoir, respectively: household ponds in Ethiopia, ndiva systems in Tanzania and combinations of mechanized zaï, grass strips and bunds in Burkina Faso. The impact of non-adapted WHTs was below expectation. Although WHTs improved yields, most families were unable to meet their (nutritional) food needs every year and experienced limited or no long-term effects on sustainable livelihood. The lining of household ponds and conveyance canals with durable materials gave promising results, yet needs economic consideration; a minimum investment may form a barrier particularly to resource-poor farmers. Incorporation of the location-specific nature of farming and livelihoods into WHT interventions is recommended, along with incentive measures to support farmers including the provision of access to credits and inputs for agricultural production.

Keywords Ponds · Ndiva · Zaï · Bunds · Arid and semi-arid areas

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D. Snelder (✉)
Centre for International Cooperation (CIS), Vrije Universiteit (VU), Amsterdam, Netherlands
e-mail: d.j.r.m.snelder@vu.nl

F. Kahimba
Sokoine University of Agriculture (SUA), Morogoro, Tanzania

O. Korodjouma
Institut de l'Environnement et de Recherches Agricoles (INERA), Ouagadougou,
Burkina Faso

A. Abebe
Arba Minch University, Arba Minch, Ethiopia

E. Oughton · L. Bunclark
Newcastle University, Newcastle Upon Tyne, United Kingdom

R. Lasage
Institute for Environmental Studies (IVM), Vrije Universiteit (VU), Amsterdam, Netherlands

W. Leal Filho and J. de Trincheria Gomez (eds.), *Rainwater-Smart Agriculture in Arid and Semi-Arid Areas*, https://doi.org/10.1007/978-3-319-66239-8_6

1 Introduction

One of the major challenges for Africa is to address the vicious cycle of poverty and food insecurity by promoting agricultural growth in general and increasing productivity per unit area in particular. Earlier studies (CA 2007; World Bank 2007) reveal that farmed areas that rely on natural rainfall rather than irrigation for water have significant potential to be improved thus increasing agricultural productivity. This is especially the case in rural semi-arid and arid areas of sub-Saharan Africa. At present, the productivity in these areas is constrained by highly variable rainfall and frequent dry spells, making rainfed farming a risky undertaking. An estimated 70–85% of the rainfall on sub-Saharan dryland farms is lost through non-productive evaporation, surface runoff and deep percolation (Rockström 2000).

Water harvesting technologies (WHTs) represent a key intervention to control water losses and strengthen productivity of rainfed agriculture in these areas. Mekdaschi Studer and Liniger (2013, p. 4) define water harvesting as, “the collection and management of floodwater or rainwater runoff to increase water availability for domestic and agricultural use as well as ecosystem sustenance”.

The harvesting of rain, runoff and floodwater for enhanced crop growth is a key strategy through which increased sustainable food production and security can be achieved in semi-arid and arid regions of sub-Saharan Africa. WHTs have been traditionally used in these regions (e.g. Critchley and Gowing 2012) where either pure rainfed or full irrigation agriculture was not an option for a number of socio-economic (e.g. lack of capital and resources), topographic and biophysical reasons (e.g. distance to water source, drought and soil constraints; e.g. Rockström and Falkenmark 2015). WHTs are particularly important in bridging dry spells, which, in turn, can lead to significant increases in productivity. For example, Bouma et al. (2016) found an average yield increase of 80% based on a meta-analysis of 221 field studies of crop yield impacts of water harvesting in semi-arid Africa and Asia.

However, the applicability and impact of water harvesting vary with technologies and local conditions. For example, Mekdaschi Studer and Liniger (2013) report a clear increase in yield and income in areas where floodwater harvesting is practised, whereas such an improvement is not always evident in areas where other forms of water harvesting are used (i.e. macro- and micro-catchment water harvesting and rooftop water harvesting). Their findings are based on an analysis of 60 case studies of water harvesting worldwide derived from WOCAT (2012).

In order to sustainably enhance food production and security, now and in the future, there is a need for WHT adaptation to account for environmental, economic and demographical changes. This chapter reports on some of the main findings of the EU-funded project “WHaTeR” (2011–2015) set up to contribute to the development of sustainable WHTs for strengthening rainfed agriculture and rural livelihoods in sub-Saharan Africa (Critchley and Gowing 2012).

The main objective of this study was to examine technology adaptation of selected WHTs in order to enhance their potential contribution to food security and livelihood improvement in the sub-Saharan region. Technology adaptation refers to a technology that is changed (improved) and tested so as to become suitable to a new condition (associated with environmental, economic or demographical changes). The following questions were addressed: what is the current status (performance and constraints) of the selected WHTs, what is their impact on food security and livelihood and what are the effects of (farmer-directed) field interventions aimed at technology improvement of the selected WHTs? The WHTs in this study included micro- and meso-scale reservoirs that store water in the soil (in situ) or in a reservoir, respectively, with or without a combination of fertilization and soil management technologies: household ponds in Ethiopia, ndiva systems in Tanzania and combinations of mechanized zaï, grass strips and bunds in Burkina Faso.

The sections below begin with an overview of the sites and the selected WHTs in the case study countries, followed by the main results of the current WHT status, the impact on food security and livelihood and the field interventions for technology improvement, based on the data gathered at multiple sites in the three countries. The main results lead to the discussion and finally the conclusion.

2 Methodology

2.1 Study Area

The study was conducted between 2011 and 2015 at multiple sites in three countries representing different parts of the sub-Saharan region, i.e. Ethiopia in the northeast, Tanzania in the east and Burkina Faso in the west of Africa (Fig. 1: location in study sites in three countries in one map). The criteria for country selection were the presence of WHTs and the presence of sites with distinct hydrological, biological and socio-economic conditions representative for sub-Saharan Africa, including lowland and upland areas in east and west Africa.

2.1.1 Climatic Conditions

Semi-arid-to-arid conditions prevail in all three study areas (Table 1): the average annual rainfall is in the range of 500–1100 mm, with the highest values recorded for Péni in Burkina Faso and Alaba in Ethiopia and the lowest for Makanya in Tanzania (Table 1). Yearly potential evaporation rates greatly exceed annual rainfall depth, indicating water deficiencies during at least part of the year. The longest dry season (up to eight months) is noted for Boukou in Burkina Faso where uni-modal rainfall patterns occur. The latter means that most rainfall is concentrated in a relatively short period with the rest of the year virtually dry. Similar conditions of water deficiency occur in the study area in Tanzania (Makanya and Bangalala),

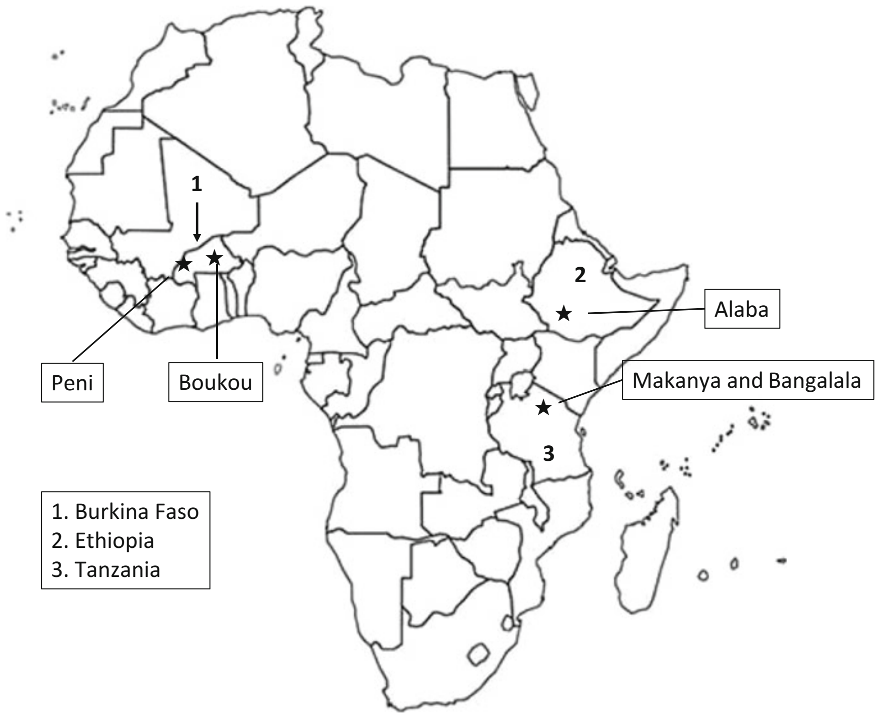

Fig. 1 Location of the study sites in Ethiopia, Tanzania and Burkina Faso

Table 1 Overview of the case study areas and associated climatic conditions in each of the three countries in sub-Sahara Africa

Climate variable Case study area	Rainfall pattern (uni or bi-modal)	Average rainfall (mm y^{-1})	Length dry season (months)	Average potential evaporation (mm y^{-1})
Ethiopia				
Alaba	Bi-modal	850–1100	7	1750[a]
Tanzania				
Makanya/Bangalala	Bi-modal	500–630[b]	6	>2000[c]
Burkina Faso				
Boukou	Uni-modal	600–900	8	1600–2000
Péni	Uni-modal	1000–1100	5	1000–2800

[a] Shewangizaw and Michael (2010)

[b] For whole Makanya catchment, the 1960s to 1990s average is 500–630 mm based on same station; Mul et al. (2006)

[c] Sally (2010), Mul et al. (2006)

although here the duration of the dry season is shorter (i.e. six months) and rainfall is distributed over two, rather than one, seasons.

2.1.2 Water Harvesting Technologies

The study addressed different types of WHTs in each of the three countries (Table 2). The criteria for selecting WHTs included: a common occurrence within a country; the need for improvement; opportunities for uptake and upscaling; and the inclusion of a range of water harvesting technologies that store rain and runoff water either directly in the soil or in reservoirs of different size and format, constructed inside or outside the cultivated fields, or a combination of both.

In Ethiopia and Tanzania, the selected WHTs were meso-reservoirs mostly located outside the fields supplemented with the reservoir water. In Ethiopia, the focus was on household ponds owned or managed by individual farmers (pond storage capacity: up to 300 m^3). In Tanzania, the so-called ndiva was object of study, supplying water to multiple fields of various households or a community (pond storage capacity: up to 2000 m^3). In *Burkina Faso*, the study covered small-scale WHTs combined with soil fertility and management technologies (WHT^+): in situ storage measures (earth bunds, stone bunds, grass strips), infield micro-reservoirs (mechanized zaï, also called planting basins or pits) and organic, compost and/or NPK and urea fertilization. The combination of technologies was tested based on reports in the literature that more promising yields can

Table 2 Overview of the water harvesting technologies selected for field studies between 2011 and 2015 and classified by country and type of water storage

Country	Type of water storage[a]	Water harvesting technology
Ethiopia	Meso-reservoir storage outside field	Household pond[b]
Tanzania	Meso-reservoir storage outside field	Dam with reservoir and canals (ndiva system)[c]
Burkina Faso	In situ storage	Earth bunds[d] with contour ploughing
	Micro-reservoir storage inside field, in situ storage	Mechanized zaï[e] with stone bunds[f]
	Micro-reservoir storage inside field, in situ storage	Mechanized zaï[e] with grass strips[g]

[a] With size details in numbered footnote

[b] Household pond volume: 30–300 m^3 (see, e.g. Tesfay 2011); ratio catchment : crop area > 5

[c] Reservoir volume of 200–2000 m^3; ratio catchment area : crop area > 5

[d] Earth bund width: 80 cm, height: 30 cm; spacing: 33 m; ratio catchment : crop area <5

[e] Micro-reservoirs, also referred to as micro-catchments or pits, with diameter of 24–30 cm and depth of 15–20 cm; ratio catchment : crop area < 2

[f] Spacing stone bunds: 30–50 m, depending on soil and slope

[g] Grass strips: 1–4 rows of *Andropogon gayanus* per strip with row spacing of 10 cm; strip spacing: 30–47 m; ratio catchment : crop area < 5

note The ratio catchment : crop area after Critchley and Gowing (2012) be achieved by combining water harvesting with fertilizer application (e.g. Winterbottom et al. 2013).

2.2 Methods

2.2.1 Case Study of Household Ponds in Ethiopia

The study in Ethiopia was conducted in the Alaba district (woreda), located in the Southern Nations, Nationalities and Peoples Regional state (Fig. 1). Water deficits affect food production in the district, whereas geo-environmental conditions hinder access to supplementary water sources; surface water is too far away for most villages while groundwater levels are generally at a depth of over 200 m (Abdela 2014). Hence, household ponds are expected to form (part of) a solution to the water deficit in the district, providing nearby water for domestic purposes, livestock watering and small-scale supplemental irrigation of crops (fruits and vegetables) during short dry spells in the growing season. However, multiple cases of pond failure (due to, for example, poor location and construction) are reported in the literature (e.g. Rämi 2003; Lemma 2005; Segers et al. 2008; Moges et al. 2011; Lasage and Verburg 2015).

A total of 145 household ponds (average storage capacity: 60 m^3) were selected in twelve municipalities of the Alaba district to assess the current status of ponds and test methods for reducing pond seepage and evaporation losses. At the start, information was gathered among pond holders (36 with concrete pond, two with geo-membrane pond and the rest—60—with earthen pond) on the current status of ponds and methods for pond improvement. Then, detailed measurements were taken on a selected number of ponds, i.e. nine cement-lined, nine geo-membrane and two earthen household ponds from three municipalities. In addition, an on-farm 72-day experiment was set up in the municipality Wanja (Alaba district) to study the water storage efficiency of square ponds with different lining materials: two lined with clay soil (sandy clay loam; pond storage capacity: 83 m^3), two lined with termite-mound soil (sandy clay loam; 83 m^3), two lined with soil and cow dung (sandy loam; 83 m^3), one lined with cement (47 m^3), one lined with geo-membrane (56 m^3) and one control pond (no lining material used; 83 m^3).

An additional survey was conducted among a total of 300 pond-holding households with good (154 interviews) or poor market access (146 interviews) to determine households' socio-economic condition and their perception of pond benefits and constraints (particularly in terms of livelihood and food security), pond maintenance and pond continued existence.

2.2.2 Case Study of Ndiva Systems in Tanzania

The ndiva system in Tanzania is typically practised in areas with frequent dry spells and increased pressure on water resources due to a growing population. It consists of a reservoir, an embankment or micro-dam, and a system of canals to convey water from reservoir to field. The reservoir allows temporary storage of rain and runoff water for supplemental irrigation. The micro-dam, built at the lower side of the reservoir from earth (usually soil excavated for reservoir construction) or concrete material, serves to increase the storage volume of the reservoir. The latter may range from 200 to 1600 m^3 (Mul et al. 2011). Located outside the cropped fields and adjacent to high or midland areas, the ndiva reservoir can harvest water also at times when there is no rainfall in the cropped area itself (Gowing et al. 1999). Various studies (e.g. Hatibu et al. 2000) report, however, problems of water losses due to evaporation and seepage and siltation, affecting the ndiva system capacity and hindering the provision of water to all farm fields and households in need.

The study in Tanzania was conducted in the Makanya catchment, Same district (Kilimanjaro Region, northern Tanzania; Fig. 1). The farmers of Bangalala village (located in the highlands upstream of Makanya village) store headwater streamflow in small-scale ndiva reservoirs overnight for irrigation of all crops during the next day, using the associated conveyance canals. However, the ndiva system suffers from conveyance losses that occur when water is being transmitted through the irrigation canals. These losses can be as high as 80%, implying that downstream fields located at long distances from the micro-dam reservoir may receive only 20 mm per field per season which is insufficient to overcome seasonal dry spells (Makurira et al. 2007). The average distance between a ndiva reservoir and associated fields supplied with water is 500 m (range: 30–3000 m). Depending on the reservoir's storage capacity and the canals' efficiency in conveying water from the reservoir to the fields, a ndiva system can serve one or more villages and irrigate an area of 50–150 ha.

The field interventions on the ndiva system, aimed at reducing the water losses from conveyance canals, were conducted between July 2012 and June 2014 in the semi-arid midlands and lowlands of the Makanya catchment. Firstly, the existing ndiva systems were examined in more detail in order to better assess current constraints. Based on this knowledge, methods for technology improvement were developed in consultation with local communities. These included innovations for increasing the system's functional efficiency such as the lining of the conveyance canals by stone pavements for which local communities provided in-kind contribution. V-notch weir and float methods were used to measure canals flow discharge while the waterfront was used to get the estimates of the velocity of water in the canals. Structured questionnaires and focus-group discussions were conducted to evaluate farmer's knowledge and perceptions on the performance, operation, maintenance and effects of the ndiva systems.

2.2.3 Case Study of Combinations of Mechanized Zaï, Grass Strips and Bunds in Burkina Faso

Burkina Faso has a long history of governmental and non-governmental organizations actively promoting the use of soil and water conservation technologies, including water harvesting through earth bunds, stone lines and zaï pits (used solely or in combination). The popularity of WHTs among organizations in, for example, the 1970s and 80s was attributed to WHTs providing visible improvements to agricultural productivity in the short term and organizations receiving external support for the construction of water harvesting structures (Kaboré and Reij 2004). Yet, WHT performance, uptake and impact remained below expectations in various parts of the country, suggesting farmers not always shared the organizations' optimistic views on WHTs. This notion led to on-farm experimentation, i.e. a process whereby WHT testing is undertaken on farmers' field for local adaptation and improved performance, which eventually can lead to a more widespread uptake.

The case study in Burkina Faso addressed a combination of small-scale WHTs including mixed micro-reservoir and in situ storage of rain and runoff water for impact maximization in terms of food production and livelihood. Household surveys were conducted to examine the current status, in terms of (lack of) uptake and adoption of the different water harvesting technologies, and their impact on food security and livelihood, at two sites in two distinct climate zones: Boukou in a lower rainfall zone (centre region) and Péni in a higher rainfall zone (south-west region; Table 1). Based on the outcomes of the surveys, on-farm tests were conducted at each site for different technology combinations (WHT^{+}) including water harvesting (mechanized zaï), fertilization, bunding (earth and stone bunds). Effects on soil quality and crop yield were assessed and associated costs and benefits of the different technologies were determined.

The combinations of technologies used for on-farm testing (Fig. 2) include:

- *Mechanized zaï* (MZ; diameter: 24–30 cm; depth: 15–20 cm) made with the use of a small (8 or 12 mm) ripper drawn by cattle or a donkey, in association with *stone bunds* (CP) along the contour line across fields with a spacing of 30–50 m, the exact distance depending on slope and soils type;

Fig. 2 Field with grass strips (left), mechanized zaï (middle) and zaï with stone bunds (right), Burkina Faso. *Photographs* Issa Ouedraogo and Korodjouma Ouatarra

- *Mechanized zaï* (MZ) constructed in combination with *grass strips* (BE) of *Andropogon gayanus* along the contour line across fields with a spacing of 30–47 m between strips and one to four rows (row spacing: 10 cm) of *A. gayanus* per strip;
- *Earth bunds* in association with *contour line ploughing* (ACN).

The criteria for selection of water harvesting, fertilization and soil management technologies included: the presence of stones or *Andropogon gayanus* grass (the former determined by geological formation, the latter by climate); the technologies indicated on the soil and water conservation technologies map for the area; the evaluation results of research institutes (Zombré 2003; Zougmore et al. 2004); the WHaTeR's revisit study (Critchley and Gowing 2012); and the farmers' preference as the last weighting criteria (farmers choice determined at last the technologies to use).

3 Results

3.1 Household Ponds in Ethiopia

3.1.1 Current Status

Figure 3 shows examples of the three types of ponds assessed in this study, i.e. concrete (with or without cover), geo-membrane plastic and earthen household ponds.

It should be noted that only two households had ponds with geo-membrane plastic lining material at the time of data collection. Moreover, households reported that none of the earthen ponds (4000 in total) installed through a government programme between 2003 and 2006 were still in use; the ponds were converted into cultivated land or used as garbage pit (Abdela 2014). The ponds were to be cemented at a later stage (requesting ca 1200 kg cement per 60 m^3 pond; Abdela 2014). However, just 10,000 quintal (1,000,000 kg) of cement was delivered, which was partly used for other purposes, resulting in the construction of only 198 concrete household ponds due to cement shortage. The remaining were left as "earthen" ponds, which in time were functioning poorly (Abdela 2014). The study revealed other factors that limited pond performance, explaining why many ponds were not in service or functioning far below capacity (see Table 3). The reason for pond adoption failure, most often reported by households, was insufficient or no involvement of communities during the pond planning and implementation processes.

Fig. 3 Household ponds in Alaba, Ethiopia: a trapezoidal pond lined with geo-membrane. Plastic for seepage control (upper left); a recently established earthen pond (upper right; a concrete pond with corrugated iron cover to reduce evaporation losses (lower left) and a non-functioning concrete pond without cover (lower right). *Photographs* Adana Abebe Awass and Hussen Abdela

3.1.2 Impact on Food Security and Livelihood

The promotion of household ponds through government programmes has been a government strategy since the late 1990s (e.g. Seyoum 2003; Rämi 2003) to alleviate poverty, improve livelihood and enhance food security among smallholder farmers. In this study, the households with a concrete pond produced for the market, whereas those with other ponds, or with non-functioning ponds, only produced for household consumption. The main crops grown with pond water included cabbage, pepper, onion, coffee, potato, avocado, mango and chat. Among the 155 households living near a road, 89% believed that a pond increases yields; 74% believed that it improves food security; and 82% believed that it improves the value of crops; for the 145 households living far away from a road, the results were less positive, i.e. 56, 65 and 65%, respectively. Households referred to pond benefits not only in terms of higher crop revenues but also in terms of savings from noticeable reductions in labour costs due to improved access to water (no need to fetch water from distant sources).

Yet, despite perceived yield benefits of ponds, 49% of the 300 households in total lost most of their harvest once every two years due to lack of (rainfall) water;

Table 3 Factors limiting the performance of household ponds in the Alaba district, Ethiopia

Limiting factor	Description
Pond location	Some ponds were located above (at higher elevation) the runoff generating area Some ponds were fed with sediment-rich water originating from catchments with a steep gradient, resulting in siltation and reduced pond capacity
Pond construction	Inappropriate use of construction material (e.g. cement for non-pond purposes leading to cement shortage and poorly lined reservoirs (Fig. 3—lower right)) From the sample of 36 households with a cement-lined pond, 76% were not functional at the time of data collection (Abdela 2014)
Water loss	Ponds suffered from leakages and, except for ten ponds constructed by Sasakawa global (Fig. 3—lower left), no pond had a cover to control evaporation
Water abstraction device	Lack of safe water abstraction mechanism; no ladder nor steps to access the water in the pond; use of traditional water lifting systems (bucket and rope)
Fencing	Household ponds were not fenced leading to accidents with livestock and children and affecting water quality where drowned animals were left to decay
Pond maintenance	70% of the households in this study did not clean their pond at all Silt traps decreased 0.7 m in depth on average, some being totally silt-covered Various ponds spread poor odour due to stagnation of water on cover sheet Use of corrugated iron covers and geo-membrane plastic sheets was less than expected, the materials being "stolen or used for other purposes" (e.g. roofing; Fig. 4) or "damaged and removed" (hyena's accessing ponds for drinking destroyed geo-membrane sheets)
Community involvement	Insufficient involvement of communities in pond planning and implementation resulting in a lack of ownership, maintenance and public awareness

on average, € 147 (stand deviation: 118) is being lost per household in a year. As coping strategies, 64% of the households grow at least four different crops, 61% practise consumption reduction and 28% engage in off-farm activities to generate extra income when there is drought or lack of rainfall. Only 55% of the households had access to credit and only 24% received remittance from relatives or close friends. Nevertheless, after witnessing economic benefits among pond adopters, most farmers were motivated to construct ponds even without assistance from the government.

The study also examined factors influencing continued existence of household ponds, i.e. whether a pond is still functioning at some time (e.g. one year or more) after initial adoption. Both "trust in authorities" (79–86% of the households; this variable was included based on reports of project successes and failures affecting households' trust in authorities) and the perception of ponds reducing risks of crop losses (75–89%) have a significant impact on the likelihood that a pond is still functioning, as is the number of livestock (Tropical Livestock Unit) owned by a household (average TLU: 4.6 and 6.6 for, respectively, households far away from any road, i.e. with poor market access, and those near a road, i.e. with good market access). Moreover, ponds financed by the government are maintained less well than ponds financed by NGOs or the households themselves. Other factors with significant impact on continued pond existence relate to pond quality (i.e. lining and maintenance of pond), technology perception (i.e. a pond reduces crop loss), location near a road and perceived market access. Non-lined ponds fall apart more easily and non- or poorly maintained ponds become dysfunctional. The importance of "location near road" is also evident from the 66% of the ponds near a road still functional as opposed to only 33% of those located far from a road. Finally, perceived market access ("good" according to 62% of households near a road and 28% of those far from road) proves to be important for longer-time pond adoption, allowing farmers to shift to the production of higher value crops in order to increase their income.

3.1.3 Pond Improvement: Use of Different Lining Materials

The 145 household ponds selected for status assessment (Sect. 3.1) differed in lining materials, i.e. concrete (cement), geo-membrane plastic and earth, resulting from different projects operating in the past. Compared to concrete lining material, geo-membrane plastic was relatively cheap and easier in application (i.e. requesting no technical expertise).

The results of on-farm testing of different lining materials in ponds, reconstructed with the assistance of farmers from previous non-functioning ponds, are presented in Fig. 4.

Concrete and geo-membrane lined ponds had higher storage efficiency than ponds with locally available lining materials, e.g. termite-mound soil. Storage efficiency decreased, with increasing seepage and evaporation losses over the test 72-day period, from 100 to 97% for geo-membrane ponds, 84% for cement ponds, 28% for ponds lined with termite-mound soil, 24% for those lined with clay soil, 19% for those lined with soil–cow dung and 12% for the control pond. Cumulative seepage losses were the highest for ponds lined with soil and cow dung (63–65 m^3) and the lowest for ponds with cement (4 m^3) and geo-membrane plastic (0 m^3); the loss from the control pond was 70 m^3. The seepage losses were measured by continuous monitoring of water levels in the household ponds and evaluating the associated water balance. Cumulative evaporation losses were the highest (3.89 m^3) for ponds lined with termite-mound soil and the lowest (1.02 m^3) for those with cement. The evaporation losses, measured with pan evaporimeter installed in the surrounding area, varied among treatments mainly due to the difference in surface area at different levels of the pond.

Total costs (including costs for labour and materials made in 2013) and effective costs (per m^3) varied from, respectively, € 154 and € 10 for ponds lined with soil

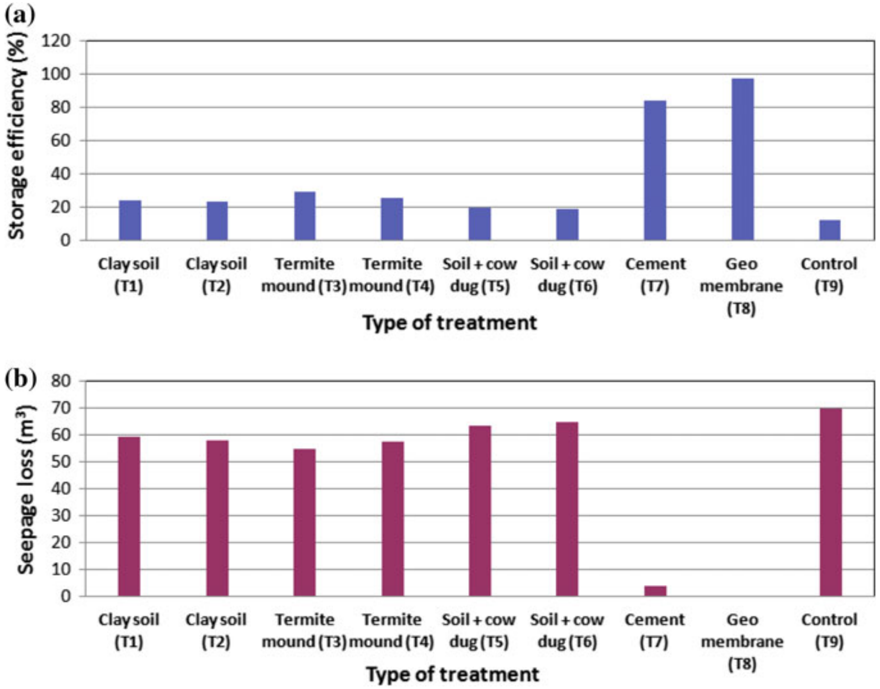

Fig. 4 Type of pond treatment (different lining materials) and corresponding **a** storage efficiency (%) and **b** seepage loss (m^3) for ponds tested over 72 days in Alaba district, Ethiopia

and cow dung, to € 209 and € 9 for ponds with termite-mound soil, to € 226 and € 12 for ponds with clay soil, to € 511 and € 18 for ponds with cement, to € 619 and € 16 for ponds with geo-membrane plastic. The effective cost is the total cost per volume effectively utilized (effectively utilized volume is calculated from the product of the total storage volume and storage efficiency). Costs for materials were € 22–23 for average-sized ponds made with locally available materials and € 358 and € 548 for those made with, respectively, cement and geo-membrane. Labour costs were 86–90% (€ 133 to € 203) of the total cost for ponds reconstructed with locally available lining materials; significant cost reduction occurs where work is done by owner and neighbouring families.

3.2 Ndiva Systems in Tanzania

3.2.1 Current Status

In 2011, the ndivas in the Makanya catchment, i.e. Manoo, Ndimka, Kavengele and Makanya, were still in operation. However, the Kavengele ndiva had not been well maintained resulting in high rates of water loss through leakage and seepage (Mahoo et al. 2012). Constraints were also reported for the Manoo ndiva, confirming the observations of Makurira et al. (2007). Most interventions to enhance water availability and increase agricultural production had been undertaken by external stakeholders targeting investments in irrigated agriculture rather than rainfed farming and ndiva systems. Attempts to enhance the capacity of water storage reservoirs and reduce conveyance losses had not been successful. Yet, in recent years, both technical assistance for ndiva improvement and farmer training on improved cultivation techniques have led to more effective use of water in fields.

The assessment study revealed four main reasons why the dam reservoirs, associated canals in the Makanya catchment suffer from capacity as well as social constraints (see also Critchley and Gowing 2012; Senkondo et al. 1999; SWMRG 2001a, b):

- Sizes of micro-dams are kept limited to avoid dam failure (both construction method and materials used hinder construction of larger dams);
- Water is wasted (due to seepage and evaporation) in both the reservoir and the unlined canals conveying water from its source to the reservoir and from the reservoir to the fields;
- Lack of financial resources impede dam construction and rehabilitation;
- Siltation occurs in water collection chambers and reservoirs due to poor management of catchment areas and water sources.

The payback period of a ndiva system is about two years, and the benefit-cost ratio 1.21. Whereas the initial investment cost is usually paid by local governments —through their District Agricultural Development Plans (DADPs)—and contributions from communities, the annual operations and monitoring are done by the beneficiary communities themselves.

3.2.2 Impact on Food Security and Livelihood

Agriculture plays a key role in meeting food needs among households in the Makanya catchment, directly through cultivation of food crops such as maize and beans and indirectly through cultivation of cash crops (e.g. *Lablab purpureus* or lablab-bean), whose profits are used to purchase food. Hence, lack of rain and erratic rainfall are perceived as the most constraining factors in achieving and maintaining food security as both livestock and crop production depend on rain. Adoption of ndiva systems can help households overcome such constraints and improve food production, yet, its effect on sustainable livelihood on a longer-term basis proved limited so far (Table 4).

Table 4 Effects of ndiva system on crop yield, food security, livelihood and water allocation based on the perceptions of households surveyed in the Makanya catchment study, Tanzania

Indicator	Effect
Yield	During times of scarce rainfall, households that have adopted ndiva systems enjoy significantly higher yields from their fields compared to those with fields depending on direct rainfall only; yet, women generally receive lower proportions of yield benefits compared to men, with men (husbands) often controlling their access to harvest; women benefitted primarily by deception, i.e. by theft of small harvest portions to be given to a friend to store for later consumption, or for sale to acquire cash to meet household or personal non-food needs
Food security	Households that have adopted ndiva systems experience improved food security and well-being "from year to year", except for those with distant fields mostly out of reach of the ndiva system and hence affected by fluctuating yields due to changes in rainfall
Livelihood	Despite the adoption of ndiva systems, households experience limited contributions to sustainable livelihoods on a more long-term basis as the unreliability of rainfall and associated variation in annual crop yields make it difficult for households to plan ahead and properly budget the use of their harvest; for women, benefits are, in general, lower due to the lack of ability to sell agricultural produce when in need, with casual labour (e.g. on sisal plantations) and savings groups contributing more significantly towards livelihood outcomes than agriculture
Water allocation	There is a high level of organization of water allocation: more or less all farmers within the ndiva system were given equal opportunities to receive water except for those with unlined canals and distant fields not reached by water from the canals during times of low rainfall

3.2.3 Ndiva Improvement: The Lining of Conveyance Canals

The lining of conveyance canals entailed the construction of a stone pavement around an earth (unlined) canal (Fig. 5). The material costs were € 1613 (TZS 3,900,000) per 100 m lined canal. It took 17–20 days (by three skilled and three semi-skilled labourers for, respectively, € 3.30 and € 6.20 per person per day) to complete 100 m of lined canal. The lining of canals was investigated because it not only can minimize water losses and shorten water travel time but it also can save time for irrigation by allowing the release of a considerable amount of supplemental water within a short time span to grow crops. High distribution efficiency, with conveyance efficiency rising from 22 to 70% (Table 5), further implies a greater potential for yield increase and long-term sustainable livelihood among farmers with lined conveyance canals (Fig. 6), compared to those using unimproved systems or no ndiva systems. Moreover, relatively larger benefits can be expected for farmers with distant fields previously not reached by water conveyed through unlined canals from dam reservoirs. In order to support dissemination of these findings, the positive performance of lined canals was shared with district officers who incorporated the project findings into the District Agricultural Development Plans (DADPs), assuring ownership of the interventions by the beneficiary farmers (Kahimba et al. 2015).

Fig. 5 Improved, lined irrigation canals to transfer water with minimum conveyance losses and shorter time from dam reservoir to field, Bangala, Tanzania. *Photographs* Sokoine University of Agriculture, Tanzania

Table 5 Performance indicators measured for lined and unlined conveyance canals in the Makanya catchment, Same district (Kilimanjaro Region), northern Tanzania

Indicator	Result
Conveyance efficiency[a]	As much as 70% of the water released from a micro-dam reached the end of a 400 m canal that had been lined, while this was only 22% for a 400 m unlined canal
Water travel time	Water running from micro-dam to fields using innovated canals reached its destination six times faster than before when unlined canals were used; a farmer with field along a lined canal had to wait for less than one second for the waterfront to reach his field (counted from the time the waterfront was one metre away); a farmer with field along an unlined canal had to wait more than four seconds
Flow velocity[b]	1.46 m s^{-1} for lined canal and 0.24 m s^{-1} for unlined canal
Distribution efficiency[c]	Compared to unlined canals, the lined canals allowed farmers to irrigate larger field areas for a given time allocation and also fields located further away from the reservoir, while using the same amount of water stored in the dam reservoir

[a] *Conveyance efficiency* [water received at field inlet (m^3)/Water released at micro-dam (m^3)] × 100%

[b] Measured over one-metre distance, starting when waterfront was at 1 m distance from field inlet

[c] Irrigated area per volume of water stored in dam reservoir per time unit

3.3 *Combinations of Mechanized Zaï, Grass Strips and Bunds in Burkina Faso*

3.3.1 Current Status

Whereas some of the WHTs tested in this research have been practised traditionally (e.g. earth bunds), others were introduced via external agents in the southern region, such as the stone lines and zaï pits at the Péni site. Intra-seasonal dry spells pose the

Fig. 6 Maize growth performance in (left) lined canal-supplemented fields (water from dam reservoir) compared to (right) rainfed fields during Masika season in Bangalala village. *Photographs* Sokoine University of Agriculture, Tanzania

greatest risk to crop production and food security across all types of household at the study sites. Hence, farmers tended to adopt a variety of water management methods in their fields to capture rainwater, reduce runoff and encourage infiltration for increasing available crop water and overcome dry spells (e.g. vegetated bunds, zai pits). In some cases, however, when wet conditions prevail, farmers had to divert runoff away from their fields in order to prevent crop loss due to runoff and flooding.

The adoption of WHTs was not as widespread as expected based on the notion that intra-seasonal dry spells pose the greatest risk to crop production and food security. Reduction of crop risk provided by WHTs was not considered sufficient to warrant the technologies' adoption by farmers without first having secured access to a range of other agricultural assets (e.g. fertilizers, high-quality seed). Farmers with higher dependence on agriculture for income and better access to agricultural inputs adopted a wider range of WHTs across more fields compared to those with lower dependence on agriculture and more limited access to inputs (see also Boyd and Turton 2000; Barry et al. 2008).

3.3.2 Impact on Food Security and Livelihood

In terms of impacts, there was no evidence of farmers in the case study sites obtaining 100–200% increases in yield, as reported by FAO (2002, 2003). Similarly, there was no evidence of significant improvements in wealth or any other livelihood outcome across households using the water harvesting technologies. On the contrary, few households meet their food needs through crop production alone, even in average or good rainfall years when using WHTs; yet, the crop gains that did occur as a result of the WHTs contributed to food security. The latter was primarily in terms of increased quantity of food (i.e. calorific value), across all typologies of household, as WHTs were primarily used in conjunction with staple cereals (sorghum, millet and maize).

3.3.3 WHT Improvement and Impact on Soil Quality and Crop Yield

The improvement of the WHTs consisted of combining three or more different technologies (WTH$^+$) including water harvesting (mechanized zaï), bunding (earth and stone bunds), grass strips and fertilization. In general, the use of the WTHs in combination with (organic) fertilizers had a positive impact on soil quality; soil pH, organic matter, N, P and K contents increased after two years from the start of the on-farm experiment. In Boukou, P and K contents for the 0–10 cm and 10–20 cm soil horizons of plots combining water harvesting with fertilization reached about two times the total P and K, 96% of the available P and 58% of the available K contents of the control plot (Table 6). Soil organic matter contents also increased up to 70% compared to the control plot. In Péni, compost application to farms with grass strips and zaï or to farms with earth bunds and contour ploughing showed the highest increases in soil total P (i.e. between 48 and 86%) and available P (between 50 and 92% increase) for the 0–10 and 10–20-cm soil layers (Table 7). Soil N content showed a minimum of 50% increase and for OM and total K, minimum increases of, respectively, 33 and 30% were recorded. Mechanized zaï in combination with stone bunds and fertilizers gave a 250% increase in sorghum yield and mechanized zaï in combination with grass strips an 83% increase in maize yield as compared to the control.

3.3.4 Costs and Benefits of Water Harvesting, Fertilization and Bunding (WTH$^+$)

All combinations of WHTs tested by the on-farm experiments had a positive (economic) return to farmers, thus providing opportunities to enhance livelihood. At Péni, all farm plots resulted in positive financial margin with the exception of the control field which recorded a loss of F CFA 265 (€ 0.40; Table 8). Zaï pits in combination with grass strip and the use of compost were profitable on a minimum area of 1613 m^2 (0.16 ha). Each F CFA 100 invested in this field gained a production value of F CFA 120 with a profit margin of F CFA 20. At Boukou, all the experimental treatments were profitable on the plot size used in the study (2500 m^2 = 0.25 ha). The combination of “stone row + mechanized zaï + compost + NPK + urea” is the most profitable in sorghum cropping (Table 8). For this site, the technology is already profitable for an area of only 832 m^2 (Table 8). For both the centre and western regions, the use of adapted water harvesting technologies, in combination with soil fertility management, improved soil chemical properties, crop yields and farmers’ incomes. To achieve these benefits in practice, a minimum investment is needed for WHT adaptation which,

Table 6 Effect of WHTs on soil (0–20 cm) properties and sorghum yields at Boukou, centre zone of Burkina Faso

Treatments[a]	BD (g cm^{-3})	pH	P_{tot} (mg kg^{-1})	P_{avail} (mg kg^{-1})	N_{tot} (%)	MO (%)	K_{tot} (mg kg^{-1})	K_{avail} (mg kg^{-1})	Grain yield (kg ha^{-1})
Control (T0)	1.63	5.57	96.9	3.46	0.083	1.79	710	42.7	700
CP + ZM + MO + EM (T1)	1.61	5.82	141.9	3.66	0.096	1.80	2181	52.4	2034
CP + ZM + Compost + EM (T2)	1.55	5.64	229.8	6.84	0.146	2.68	1021	65.0	2159
CP + ZM + MO (T3)	1.69	6.00	152.8	5.02	0.139	2.94	1071	39.9	2680
CP + ZM + Compost (T4)	1.85	5.96	264.7	4.25	0.099	2.06	796	61.5	1956
P values	<0.001	0.08	<0.001	0.001	<0.001	<0.001	0.011	0.003	<0.001
LSD[b]	0.11	0.41	62.0	1.58	0.022	0.52	873.4	13.64	1375.8

[a] Treatments include *CP* stone rows; *ZM* mechanized zaï; *MO* organic matter; *EM* mineral fertilizer; *ACN* earth bunds and contour ploughing; *BE* grass trip; *ZM* mechanized zaï

[b] Least significant difference test

Table 7 Effect of WHTs on soil (0–20 cm) properties and maize yields at Péni, western zone of Burkina Faso

Treatments[a]	BD (g cm^{-3})	pH	P_{tot} (mg kg^{-1})	P_{avail} (mg kg^{-1})	N_{tot} (%)	MO (%)	K_{tot} (mg kg^{-1})	K_{avail} (mg kg^{-1})	Grain yield (kg ha^{-1})
Control (T0)	1.45	5.77	138.9	11.06	0.059	1.22	325.1	79.01	1826
ACN + MO + EM (T1)	1.55	5.66	148.5	13.51	0.086	1.626	436.3	61.65	2777
ACN + Compost + EM (T2)	1.47	6.16	252.9	19.12	0.095	1.845	487.1	58.97	2520
BE + ZM + MO (T3)	1.44	5.99	193.8	14.11	0.083	1.596	368.4	41.76	3114
BE + ZM + Compost (T4)	1.43	5.66	205.1	20.52	0.073	1.509	383.0	53.42	2917
P values	0.002	0.045	0.001	0.06	<0.001	<0.001	0.03	0.88	0.03
LSD[b]	0.07	0.32	57.76	7.42	0.012	0.29	111.25	86	1103

[a] Treatments include *ACN* earth bund and contour ploughing; *MO* organic matter; *EM* mineral fertilizer; *BE* grass strip; *ZM* mechanized zaï

[b] Least significant difference

Table 8 Economic impact of water harvesting technologies at Péni and Boukou, Burkina Faso

Treatments	Gross return (F CFA[a])	Benefit (F CFA)	Benefit/cost ratio	Profitability threshold (m^2)
Péni				
1. Zaï + grass strip + farmer OM[b]	89,796	56.021	1.63	1507
2. Earth bund + farmer OM	80,886	48.712	1.55	989
3. Earth bund + compost	51,990	18.615	1.21	1605
5. Zaï + grass strip + compost	54,050	19.175	1.20	1613
6. Control (no WHT)	31,010	−265	0.99	2522
Boukou				
1. Control (stone row and no fertiliser)	23,714	990	1.03	2397
2. Stone bund + mechanized Zaï + farmer OM + NPK + urea	71,614	42.891	1.88	1003
3. Stone bund + mechanized Zaï + compost + NPK + urea	89,874	59.963	2.16	832
4. Stone bund + mechanized Zaï + farmer OM	49,219	21.499	1.48	1409
5. Stone bund + mechanized Zaï + compost	65,164	35.254	1.94	1148

[a] € 1 = CFA Franc (F CFA) 655.597 or 656

[b] farmer OM: organic fertilizer made by the farmer with his own skill

however, may form a barrier particularly to resource-poor farmers. Granting access to credits for agricultural inputs will help these farmers make the necessary improvements.

4 Discussion

The impact of the WHTs in Ethiopia, Tanzania and Burkina Faso proves to be below expectation, particularly with regard to food security and livelihood improvement. Although households using WHTs reported yield improvements, most families were unable to meet their (nutritional) food needs every year and experienced limited or no long-term effects on sustainable livelihood, using various coping strategies to deal with food and other related shortages. These findings support the findings of Mekdachi Studer and Liniger (2013) analysing 60 case studies of WHTs worldwide. The returns from WHTs proved to be too small for crop production alone to lift the poorest households out of poverty.

The WHTs tested on farms in Burkina Faso seem promising, with a 250% increase in sorghum yield for mechanized zaï in combination with stone bunds and fertilizers at the lower rainfall site and an 83% increase in maize yield for the mechanized zaï in combination with grass strips at the higher rainfall site.

The yield increase at the Péni site corresponds to the average yield increase of 80% reported by Bouma et al. (2016), based on the meta-analysis of 221 water harvesting field studies in semi-arid Africa and Asia. They found the relative largest impact of water harvesting on crop yields in low rainfall years. However, Gowing (2015) found for Burkinabe conditions that the probability of achieving increases in yield of even 50% or more is rather limited (let alone an increase of 250%), when accounting for rainfall-related crop risk based on longer-term rainfall records (50 years). The outcome of their quantitative risk analysis, extended with the Aquacrop simulation model applied for Burkinabe conditions (an agroclimatic zone with mean annual rainfall of 750 mm), showed an average yield increase of 25%. Moreover, the probability of achieving a yield increment of at least 50% was below 10%. These results are in line with the large standard deviation of 84%, and the several studies reporting limited yield increases, found in the WHT meta-analysis conducted by Bouma et al. (2016). The marginal reduction in rainfall-related crop risk that the use of WHTs can provide is unlikely to lead to high adoption by farmers unless it is seen as means of recovering unproductive land.

WHT adaptation and maintenance further need a minimum investment that most of farmers do not have. Although promising, the lining of household ponds and ndiva conveyance canals with appropriate materials needs to be considered when economically justified (see Bouma et al. 2016 for an economic analysis of WHTs). The same is true for the combination of WHTs tested in Burkina Faso where minimum investment may form a barrier particularly to resource-poor farmers. Incentive measures to support farmers are needed, including the provision of access to credits for agricultural production and access to inputs such as durable lining materials, improved seeds and fertilizers.

An important factor determining the extent to which benefits had been achieved is related to the degree of community involvement and the quality of external intervention provided during the WHT planning and implementation processes. In the case of household ponds in Ethiopia, community involvement was limited or inadequate. The latter explains why the intended beneficiaries were unable to develop a sense of ownership, and often the ponds were constructed in a suboptimal location. This is in line with Awulachew et al. (2005) who linked low performance of WHT in Ethiopia to flawed project design and lack of adequate community consultation during project planning. The ponds that were constructed as part of NGO programmes or by the households themselves proved better maintained than those constructed as part of government programmes. Participatory planning and design of the runoff ponds with due consideration of local circumstances and including a watershed approach are essential (Lasage and Verburg 2015). External intervention, where applied in a sustainable and participatory manner, remains crucial for the continued existence of WHTs not only in Ethiopia but also in Tanzania and Burkina Faso. In the latter country, the adoption and expansion of WHTs have been low outside of communities supported by external interventions (Morris and Barron 2014).

5 Conclusions

Rainfed systems of crop production pose a great challenge especially in the drought-stricken semi-arid and arid areas of sub-Saharan Africa. WHTs have the potential to harvest and store rain and runoff water for use at times when there is no rain, or for bridging dry spells through supplemental field irrigation during the wet season. Successes of WHTs noted through this research relate to the creation of an enabling (policy) environment (e.g. providing credit facilities to farmers, extension services and participatory technical support) and the promotion of WHT as a package (WTH^+), together with other agricultural inputs (e.g. improved seeds and fertilizer), adapted to the local environmental, social and economic context within which they are implemented.

Failures are primarily related to the high level of unpredictability in risk reduction combined with the range of asset-related constraints that farmers experience. The most vulnerable farmers will not develop to an agricultural self-sufficiency level by solely investing in water harvesting systems, as their position is dependent on a multitude of factors (e.g. nature of asset endowment, activities engaged in and market access), of which water availability is only one. On the other hand, improving water harvesting systems for farm households that are not considered to be the most vulnerable in their region can be beneficial for enhancing their livelihood situation, especially when the additional yield can be sold on a market. There is a risk that improvement is mainly through the quantity rather than the quality of food available. WHTs are often primarily implemented to increase the production of cash crops, with the earned income being used to improve the quality of diet and other livelihood needs (e.g. medical care, schooling). Also, food security and poverty are both multi-dimensional concepts, suggesting increased crop production does not necessarily equate directly to increased food security or reduced poverty. More research on the role of WHTs in nutrition-sensitive agriculture is recommended.

Acknowledgements The research leading to these results has received funding from the European Community's Seventh Framework Programme under grant agreement number 266360 (WHaTeR).

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