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Review Article

Combining insitu rainwater harvesting and integrated nutrient management of organic manure improves soil moisture, fertility and crop yields in marginalized areas: A review

*Andrew T. Kugedera[1,2]

Affiliation
[1]Department of Agriculture Management, Zimbabwe Open University, Masvingo, Zimbabwe.

[2]Morgenster Teachers College, Department of Mathematics and Science, Masvingo, Zimbabwe

***For correspondence**: **email**: kugederaandrew48@gmail.com; **tel**: +263 78 278 8783
orcid: https://orcid.org/0000-0002-1700-6922

Abstract
Soil moisture stress and infertility are major biophysical constraints which limit crop production and food security in marginalized areas. Marginal areas are mainly associated with low rainfall which is insufficient to support crops until maturity is reached. The use of insitu rainwater harvesting methods such as planting pits, tied ridges, mulching, *Zai* pits and half-moon can be a solution to reduce moisture stress. This alone cannot improve crop yields hence the need to use integrated nutrient management (INM) of animal manure, biofertilisers, mineral fertiliser and composts to improve soil fertility, structure and increase water retention ability. Combining rainwater harvesting with INM has the potential to mitigate effects of climate change, improve crop yields and meet food demand in marginal areas. Various nutrient sources used as INM can restore soil health, increase microbial population, nutrient mineralisation and improve soil quality. Use of biofertilisers in agriculture reduces soil toxicity, improve nutrient availability and create a conducive environment for crop growth and development. Integration of tied ridges with cattle manure and mineral fertiliser has the potential of increasing infiltration rates, reducing surface runoff and increase crop yields with 50-150% regardless of soil type. This chapter sought to come up review the effects of rainwater harvesting methods and INM on soil fertility, moisture stress and crop yields in marginalized areas.

Keywords: *Tied ridges, marginalized areas, integrated nutrient management, soil fertility, soil moisture.*

INTRODUCTION
Food security in semi-arid areas of Sub-Saharan African (SSA) countries has been declining over the year due to frequent droughts and inadequate mineral fertiliser addition by smallholder farmers (Bekunda et al., 2010; Chilagane et al., 2020; Bado et al., 2022). Smallholder farmers in these areas are facing high chances of hunger and poverty enhanced by poor crop production (Bado et al., 2022). There is need to come up with sustainable crop production strategies which reduce the effects of climate change and achieve sustainable food production (Swai et al., 2023). Climate smart agriculture is the most promising farming technique that allows smallholder farmers to

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optimize farm productivities with their limited resources (Kugedera and Kokerai, 2023). Growing economic and environmental concerns in agriculture promote adoption of climate smart agriculture where farmers are encouraged to apply low quantities of organic manure. Applying low quantities of cattle manure (Sileshi et al., 2019), farmyard manure (Mwadalu et al., 2022) and compost manure (Kedar et al., 2019) restore soil fertility, improve structure, soil health and crop yields (Mamuye et al., 2021).

Organic manure needs to be coupled with mineral fertilisers to provide immediate supply of nutrients to crops. Judicious and balanced use of organic manure and mineral fertilizer alongside other relevant agronomic practices is known as integrated nutrient management which plays a pivot role in soil fertility restoration and yield improvement (Mugwe et al., 2009a; Kugedera et al., 2023a). Integrated nutrient management (INM) has been reported to improve soil health, structure, and water retention. It also improves the infiltration and decomposition of organic matter thereby enhancing the nutrient availability to the root zone. This promotes microbial activities which is also important for nutrient cycling (Gram et al., 2020; Tsujimoto et al., 2021; Kugedera et al., 2023a; Mugwe et al., 2009b; Workineh et al., 2022). Organic matter can be used as mulch for soil and water conservation since this reduce soil erosion, surface runoff and increase chances of nutrient recycling. Farmers applying 20 t ha^{-1} cattle manure meet requirements for sustainable farming system in sandy soils (Nyamangara et al., 2005). However, low and erratic rainfall (250-450 mm) received in many semi-arid areas across SSA cannot sustain crops to maturity hence the need to harvest rainwater (Itabari et al., 2004; Kugedera et al., 2022). Therefore, the combined use of INM with insitu rainwater harvesting will facilitate decomposition, increase soil water content and crop production.

Insitu rainwater harvesting (IRWH) techniques are practices that involve harvesting, storing and increased infiltration of water in the soil. Various IRWH techniques can be used in semi-arid regions, but their suitability varies with soil type and labour requirements (Itabari and Wamuongo, 2003; Nyamadzawo et al., 2013, Swai et al., 2023). Commonly used IRWH techniques include tied ridges, planting pits and infiltration pits in countries like Zimbabwe, Tanzania, Kenya, Burkina Faso, Rwanda, Mali, Niger and Ghana (Coulibaly et al., 2015; Mahinda et al., 2018; Nyagumbo et al., 2019; Chilagane et al., 2020; Swai et al., 2023). Tied ridges are ridges with cross ties at intervals and plants are grown between the ridges. Ridges are prepared with ox-drawn mouldboard plough and cross ties are done using hand hoes at intervals from 5-10 m depending on the farmer and soil type (Kugedera and Kokerai, 2023; Swai et al., 2023). Tied ridges are more effective in sandy loam to loam soils in areas with slope variation up to 3 % (Nyakudya et al., 2015). The practice was reported to increase soil water content and crop yield in Tanzania, Rwanda, Zimbabwe, Niger and Mali (Itabari et al., 2011; Motsi et al., 2004; Mudatenguha et al., 2014; Coulibaly, 2015; Gonda, 2015; Nyagumbo et al., 2019). Planting pits are also common in semi-arid areas although they are prepared on smaller pieces of land due to high labour demand Chiturike et al. (2023) reported increments in crop yields with the use of planting pits. Same report was indicated by Kimaru-Muchai et al. (2021) who obtained higher sorghum yields with the use of INM + planting pits in Kenya. Combining INM and IRWH have the potential of solving soil fertility, water content and yield issues in SSA and achieve zero hunger. Therefore, the aim of the study was to assess the effects of combining INM and IRWH techniques on soil moisture content, fertility and crop yields in semi-arid areas of SSA.

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METHODOLOGY

Data collection

The search of published data was carried out in October 2023 to January 2024 to retrieve paper from reputable indexes such as Scopus, web of science and google scholar which comprised experiments on integrated effects of insitu RWH and INM on soil water content, fertility and grain yields in marginalised across Africa. The search was restricted to combination effects of insitu RWH and INM on soil moisture, fertility and crop yields in semi-arid/ low rainfall areas in Africa. The published articles must satisfy the following: (i) articles published in reputable journals under Scopus and Web of Science (ii) field experiments carried in marginalized areas in Africa, (iii) peer reviewed and experimental season well indicated, (iv) Experiments must include insitu rainwater harvesting and integrated nutrient management and (v) published. Search was done following these keywords; integrated nutrient management/INM, insitu RWH, INM*cereal crops*SSA and insitu RWH*INM*crop yields*Africa, "INM" (Title) or "insitu RWH on soil water content" (Topic) or "INM and RWH on soil moisture, fertility and crop yields (Topic) and "INM in smallholder farmers" (Topic) and "INM and insitu RWH in marginalised areas". The review focused on semi-arid areas in SSA where rainfall received is erratic and low, soil infertility and poor crop yields which can be improved by insitu RWH and INM. The review emphasized more on low soil fertility areas which have limited water retention ability where improvements can be done through use of insitu RWH and INM. Many papers reviewed were from SSA, central and western African countries covering major crops. These areas were selected due to similarities in crops grown and use of insitu RWH techniques. Many resources constrained farmers in these countries have adopted insitu RWH techniques and INM to increase nutrient availability, soil water and grain yield. Many farmers in these countries combine mineral fertiliser, cattle manure and agroforestry biomass as INM sources. This helps to come up with great base for review and conclusions.

Three hundred (300) articles were retrieved and were selected using Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRIMSA) as shown on Fig 1. These articles were evaluated removing duplicates leaving 202 articles. All 202 papers were screened, and 80 articles failed to meet the criteria. Articles published in predatory journals and conference papers were removed leaving 122 articles. Furthermore, 50 articles had unmatching treatments, no seasonal data and some data shown in graphs, were all removed. Finally, 72 articles were involved in this synthesis.

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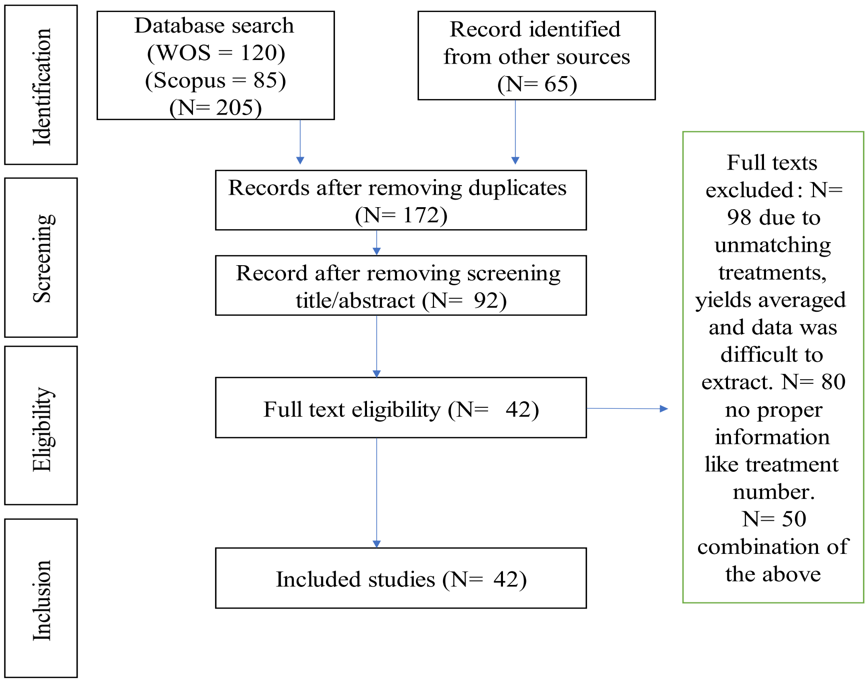

Figure 1: PRIMSA chart used for data identification and selection.

RESULTS AND DISCUSSION

Effects of insitu RWH techniques and INM on soil moisture content in marginal areas

Soil water content in marginal areas can be improved by adoption of insitu RWH techniques such as ridges, planting pits and infiltration pit. These techniques collect rainwater, hold it and recharge soil moisture. The use of insitu RWH techniques in Zimbabwe was reported to increase soil water content in marginal areas receiving little rainfall (<450 mm per season) from as low as 5.4 % to 8.3 % on sand soils (Nyagumbo et al., 2019). Tied ridges in Ethiopia increased soil moisture content from <160 mm m^{-1} to an average of 230 mm m^{-1} in sandy clay loam soils (Milkias et al., 2018). Planting pits are commonly known as Zai pits in Mali, Niger and Ghana were reported to have high soil moisture content of 9.26% on 0-20cm depth compared to 7.28% and 7.92% under conventional and tied ridges in Mali (Coulibaly, 2015). In Zimbabwe, the use of planting pits shows higher soil moisture content (13.6%) in sandy soils compared with 6.88% and 10.2% from conventional and tied ridges (Kugedera et al., 2018). Soil water content vary with soil depth in all insitu RWH techniques for example findings by Coulibaly (2015) who indicated that planting pits had 15.12% compared with 9.5% and 12.63% from conventional and tied ridges respectively.

Combination of compost and chemical fertilisers has the potential of increasing soil moisture content because compost manure improves soil porosity, structure and water retention ability. Studies done in Niger showed that application of 2.5 t ha^{-1} compost manure and 0.1t ha^{-1} compound D improve soil moisture content from 6.88% with no NPK to 7.28% with NPK (Gonda, 2015). Increasing NPK fertiliser above 100 kg ha^{-1} reduce soil moisture content from 7.28% to 6.85% with good rains and maintaining soil moisture content at an average of 3.5% with low rainfall. Combination of Zai pits and INM in Mali was reported to increase soil moisture content up to 16.73% from 20-40cm and 10.19% at 0-20cm deep on sandy-loam soils (Coulibaly, 2015). In Kenya, conservation agriculture of mulch and 60 kg N ha^{-1} from cattle manure + NPK fertiliser reduce evaporation of water in the field, increase infiltration rates and lower surface runoff hence

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increasing soil moisture content and water use efficiency (Oduor et al., 2023). A summary of combined effects of insitu RWH and INM on soil moisture is shown in Table 1.

Table 1: Integrated effects of insitu RWH and INM on soil moisture content in semi-arid areas

Country	Results	Reference
Mali	Integration of tied ridges and Zai pits with cattle manure and mineral fertiliser increased soil moisture content from 7.06% to 8.06% and 10.19% at 0-20cm depth and to 14.08% and 16.73% at 20-40 cm depth respectively. Zai pits + INM were more dominant and had higher water storage of 47.62 mm in the 0-20cm at 45 days after planting.	Coulibaly (2015)
Kenya	Combination of Zai pit with cattle manure and 30 kg N ha^{-1} increased soil moisture content in sorghum fields and this sustained crop to maturity. Integration of Zai pits with Tephrosia + 30 kg N ha^{-1} also increased soil moisture content and maintained water storage	Kimaru (2017)
Ethiopia	Biomass from Leucaena was mixed with 50% NPK (150 kg ha^{-1}) improved soil structure, aggregate stability, porosity and water retention ability thereby more soil water was gained.	Kebede et al. (2012)
Kenya	Animal manure + 30 kg N ha^{-1} added to planting pits increased soil water content which was 23% higher than conventional tillage treatment.	Kebenei et al. (2023)
Zambia	Integration of improved fallow with mineral fertiliser increased soil water retention and infiltration rates. This increased soil moisture content by more than 50%.	Kwesiga et al. (2005)
Kenya	Combination of animal manure, N fertiliser and tie ridges has the potential of increasing soil moisture content. The combination improves soil structure, water retention and increase infiltration rates.	Oduor et al. (2023)
Tanzania	Tied ridges were combined with cattle manure, mineral fertiliser and Minjingu Mazao to increase soil structure, water retention ability and soil water content in marginal area of Tanzania.	Kilasara et al. (2015)
Niger	Zai pits were integrated with organic and inorganic fertiliser with the intention of increasing soil water content, fertility and pearl millet grain yield. The treatment increase infiltration rates, soil water holding capacity and plant available water in rooting zone.	Fatondji et al. (2006)
Zimbabwe	Soil moisture content improved with tied ridges + Leucaena biomass and NPK fertiliser leading to increased crop yield even though 2019/20 cropping season received low rainfall.	Kugedera et al. (2022d)

Effects of INM on soil fertility in semi-arid areas

Integrated nutrient management practices are set of soil fertility management where farmers combine organic and mineral fertilisers. The use of INM has been regarded as one of the best soil fertility managements (SFM) practice which smallholder farmers in semi-arid areas can adopt to improve nutrient availability, regulate soil pH, increase cation exchange capacity (CEC) and soil organic carbon (Mugendi et al., 2003; Mugwe and Otieno, 2021; Odour, 2022; Kugedera et al.,

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2023c; Kugedera and Kokerai, 2024). Farmers usually combine organic manure such as cattle manure, compost and farmyard manure with small quantities of mineral fertiliser (NPK) at planting to boost basic cation availability (Kimaru-Muchai et al., 2021). This has the ability of improving soil structure hence increasing soil nutrient retention ability. Studies done in SSA, central and West Africa showed that the use of INM improve soil CEC, total nitrogen and base saturation (Mugwe et al., 2019; Sebnie et al., 2020; Mamuye et al., 2021; Workineh et al., 2022). The use of INM also use of legume tree biomass such as biomass transfer and hedgerow intercropping which are all combined with reduced quantities of mineral fertilisers. The use of INM has the possibility of reducing concentrations of toxic substances in the soils, for example addition of lime + compost reduce concentration of exchangeable aluminum in Ethiopia (Workineh et al., 2022). Combining biochar with N fertiliser have capacity improve cation exchange capacity and nutrient availability (Xia et al., 2020). Integration of organic and inorganic nutrient sources improve nutrient availability hence increasing crop yields. Organic nutrient sources contain several nutrients which are supplemented by application of inorganic fertilisers since quality of organic sources vary. This combination replenishes soil fertility by regulating pH, increase CEC and base saturation (Mugwe et al., 2009a, 2009b). Table 2 show contribution of INM on soil fertility.

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Table 2: Effects of insitu RWH, INM and their combination on soil fertility parameters in semi-arid areas

Treatment	Region	Parameters	Effects (+ or -)	References
1 t ha^{-1} lime + 3 t ha^{-1} compost	Ethiopia	Available P Exch. Al^{3+} Total nitrogen (%)	11 mg kg^{-1} (+) 0.75 cmol $_{(+)}$ kg^{-1} (-) 0.21 % (+)	Workineh et al. (2022)
2.5 t ha^{-1} Leucaena biomass + 2.5 t ha^{-1} cattle manure	Zimbabwe	Total N (g kg^{-1}) Exch. Calcium (g kg^{-1}) pH	2.3 g kg^{-1}(+) 0.101 g kg^{-1}(+) 6.0 (+)	Kugedera et al. (2023b)
5 t ha^{-1} Leucaena + 50 kg NPK	Zimbabwe	pH Sodium cmol$_c$ kg^{-1}	6.1 (+) 0.082 cmol$_c$ kg^{-1} (-)	Kugedera et al. (2022c)
260 kg N ha^{-1} + 15.5 t ha^{-1} biochar	China	Organic matter (g kg^{-1})	14.8-16.1 g kg^{-1} (+)	Wang et al. (2023)
Mineral fertiliser + manure	Namibia	Total nitrogen	Increase (+)	Hirooka et al. (2021)
5 t ha^{-1} Tobacco leaf scarp + cattle manure	Zimbabwe	Mineral N (mg g^{-1}) Available P (mg kg^{-1})	10 mg g^{-1} (+) 21.5 mg kg^{-1} (+)	Dunjana et al. (2020)
Leucaena + 30 kg N ha^{-1}	Kenya	Exch. K (g kg^{-1}) Carbon (g kg^{-1}) Total N (g kg^{-1})	0.3 g kg^{-1}(-) 16.7 g kg^{-1}(-) 2.3 g kg^{-1}(+)	Mucheru-Muna et al. (2007)
Plant biomass + manure + inorganic fertiliser	Kenya	Total N pH	Increase (+) Increase (+)	Mugwe et al. (2007)
Organic + inorganic fertiliser	Zambia	Total N	Increase (+)	Mafongoya et al. (2006)
Cattle manure + Zai pit + 30 kg N ha^{-1}	Kenya	Organic carbon	1.6 % (+)	Kebenei et al. (2023)
2500 kg ha^{-1} Cattle manure + 250 kg ha^{-1}NPK	Kenya	Potassium (kg kg^{-1}) Carbon (kg kg^{-1})	Increase (+) Increase (+)	Maluki et al. (2020)

Effects of insitu RWH techniques and INM on crop yields in marginal areas

Soil moisture and nutrient imbalances are common challenges which causes low grain yield in marginal areas (Bekunda et al., 2010; Swai et al., 2023). Cereal base production is one of the important enterprises with many farmers across the world growing maize, wheat, rice, sorghum and millets as staple crops (Xia et al., 2020; Kugedera et al., 2022c; Kugedera and Kokerai, 2023; Kugedera et al., 2023c; Wang et al., 2023). Crop production can only be increased to highest level through combination of RWH techniques and INM which address soil moisture and nutrient stress simultaneously (Kugedera et al., 2023a; Kubiku et al., 2022a). in countries like Kenya, combination of Zai pits with Tithonia (*Tithonia diversifolia*) biomass + 30 kg ha^{-1} N fertiliser improved grain yield of sorghum from 190 kg ha^{-1} to 1430 kg ha^{-1} (Kimaru-Muchai et al., 2021; Kugedera et al., 2023c). This was similar to study by Kubiku et al. (2022b) where use of tied contours + 5 t ha^{-1} cattle manure + 70 kg ha^{-1} N fertiliser raised sorghum grain yield from 400 kg ha^{-1} to 1340 kg ha^{-1} in Zimbabwe (Kugedera et al., 2022a). Grain yield of sorghum was also increased in Tanzania with the use of tied ridges +N fertiliser + farmyard manure from less than 1000 kg ha^{-1} to 5120 kg ha^{-1} in sandy clay loam soils (Mahinda et al., 2018). Other insitu RWH techniques such as ripper ploughing, ridging and infiltration pit showed increasing maize grain

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yields under INM in countries like Tanzania (Swai et al., 2023), Zimbabwe (Motsi et al., 2004; Nyamadzawo et al., 2015; Nyakudya et al., 2015; Kugedera et al., 2020) and Ethiopia (Asaye et al., 2022). Combining INM and insitu RWH has the ability of increasing nutrient absorption and plant growth leading to increased crop productivity (Sher et al., 2022). Nutrient sources used in INM improve soil water retention, reduce leaching and increase nutrient availability in the plant root zone (Kugedera et al., 2023b). Integrated nutrient management increase crop productivity when combined with insitu RWH due to positive synergistic association of water and nutrients (Kimaru-Muchai et al., 2021; Kugedera et al., 2023b). Summary of crop yields as influence by insitu RWH and INM are in Table 3.

Table 3: Interactive effects of insitu RWH and INM on crop yields in semi-arid areas of Africa

Treatments	Region	Season	Crop	Grain yield (kg ha^{-1})	References
Tied ridge + N fertiliser + farmyard manure	Tanzania	2015/16	Sorghum	5730	Mahinda et al. (2018)
Zai pit + Tithonia diversifolia + 30 kg N ha^{-1}	Kenya	2013/14	Sorghum	3960	Kimaru-Muchai et al. (2021)
Tied ridge + 30 kg N ha^{-1} + 5 t ha^{-1} cattle manure	Kenya	Long rain 2016	Maize	4100	Ndung'u et al. (2023)
Planting pit + 2.5 t ha^{-1} cattle manure + 25 kg NPK ha^{-1}	Zimbabwe	2020/21	Maize	1486	Kugedera & Kokerai (2023)
Tied ridge + 2.5 t ha^{-1} cattle manure + 25 kg NPK ha^{-1}	Zimbabwe	2020/21	Maize	1642	Kugedera & Kokerai (2023)
Tied ridge + 7.5 t ha^{-1} cattle manure + 100 kg NPK ha^{-1}	Zimbabwe	2021/22	Maize	6538	Kugedera & Kokerai (2023)
Planting pit + 7.5 t ha^{-1} cattle manure + 100 kg NPK ha^{-1}	Zimbabwe	2021/22	Maize	4980	Kugedera & Kokerai (2023)
Tied ridge + 2.5 t ha^{-1} + 20.5 N +23 P_2O_5	Mali	2013	Pearl millet	1026	Coulibaly (2015)
Zai pit + 2.5 t ha^{-1} + 20.5 N +23 P_2O_5	Mali	2014	Pearl millet	1151	Coulibaly (2015)
Tied ridge + mineral fertiliser + farmyard manure + Minjingu Mazao	Tanzania	2014	Sorghum	640-2605	Kilasara et al. (2015)
Tied ridge + 5 t ha^{-1} farmyard manure + cowpea intercrop for N	Kenya	Long rains 2015	Maize	810	Mwende et al. (2019)
Tied ridge + 10 t ha^{-1} Farmyard manure + 20 kg N ha^{-1}	Kenya	1997-2003	Maize	2536.8	Gichangi et al. (2007)
Ripping + 5 t ha^{-1} Farmyard manure + 20 kg N ha^{-1}	Kenya	2007 short rains	Maize	1710-2950	Kathuli and Itabari (2012)
Ripping +Farmyard manure + N fertiliser	Tanzania	2015/16-2016/17	Sorghum	5730 1820	Mahinda et al. (2018)
Zai pit + cattle manure + mineral fertiliser	Niger	2004/5	Pearl millet	>500	Fatondji et al. (2006)

Lessons and future directions

Insitu RWH and INM has the possibility of increasing soil water content, nutrient availability and plant productivity. The acceptance of rainwater harvesting and nutrient management by farmers in semi-arid areas has been reported to improve food security, reduce poverty and lower food prices.

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Combination of insitu RWH techniques such as planting pit and tie ridges are labour intensive and require more evaluation at different rates of INM to determine value cost ratio. Reviewed results show that application rates of manure less or equal to 2500 kg ha^{-1} and 100-150 kg ha^{-1} inorganic fertiliser have higher value cost ratio which guarantee high profits to smallholder farmers in high-risk climate areas. Besides increasing soil moisture, fertility and yields, insitu RWH and INM has the potential of improving agronomic and rainfall use efficiency. For future studies, there is need to evaluate the effects of insitu RWH and INM on rainfall use efficiency, yield sustainability, returns on investment and agronomic efficiency. There is need to determine INM rates which provide smallholder farmers in high-risk climates with higher yields which are sustainable at good agronomic efficiency and high return on investment so that they take farming as a business. This will equip these farmers with adequate information necessary to avoid dependence on food aid, input aid and improve their standards of living through farming as a business.

CONCLUSIONS

Semi-arid areas are characterised by sandy loam soils (Nitisols/Luvisols) which have low nitrogen content and are dry most of the times due to low and erratic rainfall received in these areas. Growing seasons have been shortened affected many farmers as received rains does not sustain crops to maturity, hence the use of nutrient and water management strategies. Planting pits and tied ridges proved to be major insitu RWH techniques which improve soil water content, lower water loss by surface runoff and store water making it available to all crops without being affected by slope as in case of infiltration pits. Application of cattle manure and mineral fertiliser integrated with organic nutrient sources which include compost, farmyard manure and agroforestry biomass can be a promising technique to restore soil fertility, reduce land degradation and improve crop yields. Insitu RWH makes water available to crops which can be used for absorption of nutrients, photosynthesis and growth leading to higher yields. Combining insitu RWH and INM proved to be a sustainable agricultural option which improve soil and water conservation, improve crop productivity and reduce food shortages especially in semi-arid areas.

References

Asaye Z, Kim DG, Yimer F, Prost K, Obsa O, Tadese M, Gebrehiwot M, & Brüggermann N (2022). Effects of combined Application of Compost and mineral fertilizer on soil carbon and Nutrient content, yield and agronomic Nitrogen Use efficiency in Maize-Potato cropping systems in Southern Ethiopia. Land, 11, 784. https://doi.org/10.3390/land11060784

Bado BV, Bationo A, Whitbread A, Tabo R, & Manzo MLS (2022). Improving the productivity of millet-based cropping systems in the West African Sahel: Experiences from a long-term experiment in Niger. Agriculture, Ecosystems and Environment, 35:107992. https://doi.org/10.1016/j.agee.2022.107992

Bekunda B, Sanginga N, & Woomer PL (2010). Restoring soil fertility in sub-Sahara Africa. Advances in Agronomy, 108: 184-236.

Chilagane EA, Saidia PS, Kahimba FC, Asch F, Germer J, Graef F, Swai E, & Rweyemamu CL (2020). Effects of Fertilizer Micro-dose and In Situ Rainwater Harvesting Technologies on Growth and Yield of Pearl Millet in a Semi-arid Environment. *Agric Res*. https://doi.org/10.1007/s40003-020-00454-7

https://doi/org/10.57046/HRBT3684

Chiturike P, Nyamadzawo G, Gotosa J, Mandumbu R, Nyakudya IW, Kubiku FNM, & Kugedera AT (2023) Evaluation of different rainwater harvesting techniques for improved maize productivity in semi-arid regions of Zimbabwe with sandy soils. Journal of Sustainable Agriculture and Environment, 2(1): 26-39. https://doi.org/10.1002/sae2.12033

Coulibaly B (2015). Impact of water harvesting techniques and nutrient management options on the yield of pearl millet in the Sahelian Zone of Mali [dissertation]. Kwame Nkrumah University of Science and Technology.

Dunjana N, Zengeni R, Pisa C, Wuta M, & Muchaonyerwa P (2020). Nutrient uptake, yield and taste of oilseed rape (*Brassica napus* L.*)* and soil chemical properties following amendment with uncomposted and composted tobacco waste and cattle manure. S Afr J Sci. 2020;116(9/10), https://doi.org/10.17159/sajs.2020/7846

Fatondji D, Martius C, Bielders CL, Vlek PLG, Bationo A, & Gerard B (2006). Effect of planting technique and amendment type on pearl millet yield, nutrient uptake, and water use on degraded land in Niger. *Nutrient Cycling in Agroecosystems*, 76 (2-3): 203-217.

Gichangi EM, Njiru EN, Itabari JK, Wambua JM, Maina JN, & Karuku A (2007). Assessment of improved soil fertility and water harvesting technologies through community based on-farm trials in the ASALs of Kenya', in Batiano, A. (Ed.): *Advances in Integrated Soil Fertility Management in Sub-Saharan African: Challenges and Opportunities*, Springer, pp.759–765.

Gonda A (2015). Integrated management of composted cattle manure and mineral fertilizer for improved pearl millet and cowpea yields under strip cropping system in Niger [dissertation]. Kwame Nkrumah University of Science and Technology, Ghana, pp185.

Gram G, Roobroeck D, & Vanlauwe B (2020). Combining organic and mineral fertilisers as a climate smart integrated soil fertility management practice in sub-Saharan Africa: A meta-analysis. PlosONE 15 (9), https://doi.org/10.137/journal.pone.0239552:r003

Hirooka Y, Awala SK, Hove K, Nanhapo PI, & Iijima M (2021). Effects of Cultivation Management on Pearl Millet Yield and Growth Differed with Rainfall Conditions in a Seasonal Wetland of Sub-Saharan Africa. Agronomy, 11, 1767. https://doi.org/10.3390/agronomy11091767

Itabari JK (1999) 'Optimizing soil water use in the Semi-Arid Areas of Kenya', Efficient Soil Water Use: the key to Sustainable Crop Production in Dry Areas. Proceedings of the workshops organized by the Optimizing Soil Water Use Consortium, 26–30 April, Niamey, Niger, pp.85–104.

Itabari JK & Wamuongo JW (2003) *Water-Harvesting Technologies in Kenya*, KARI. Technical Note Series No. 16, June.

Itabari JK, Kwena K, Esilaba AO, Kathuku AN, Muhammad L, Mangale N, & Kathuli P (2011) 'Land and water management research and development in arid and semi-arid lands of Kenya'.

Bationo A, Waswa B, Okeyo JM, Maina F, & Kihara JM (Eds.): *Innovations as Key to the Green*

https://doi/org/10.57046/HRBT3684

Revolution in Africa, Springer, pp.427–438.

Itabari JK, Nguluu SN, Gichangi EM, Karuku AM, Njiru EN, Wambua JM, Maina JN, & Gachimbi LN (2004) 'Managing land and water resources for sustainable crop production in dry areas: a case study of small-scale farms in semi-arid areas of eastern, central and rift valley provinces of Kenya', in Crissman, L. (Ed.): *Agricultural Research and Development for Sustainable Resource Management and Food Security in Kenya*, 11–12 November, pp.31–42.

Kader MA, Singha A, Begum MA, Jewel A, Khan FH, & Khan NI (2019) Mulching as water-saving technique in dryland agriculture: review article. Bulletin of the National Research Centre, 43(147):1-6. https://doi.org/10.1186/s42269-019-0186-7

Kathuli P & Itabari JK (2012) Effect of Tied and Open Ridge on Total Dry Matter Yield of Maize in Mwala (AEZ 4), Yatta and Kitui (AEZ 5) During Short Rains 2007, KARI-Katumani Annual Report.

Kebede D, Abdelkadir A, Asfaw Z, & Teklehaimanot Z (2012). Effects of *Leucaena [Leucaena leucocephala* (Lam.) de Wit] Leaf Biomass and NP Fertilizer Application on Soil Fertility, Striga [*Striga hermonthica* (Del.) Benth] Management and Sorghum [Sorghum bicolor (L.) Moench] Growth and Yield in Pawe District, Northwestern Ethiopia. *East African Journal of Sciences*, 6 (2): 147-156

Kebenei MC, Mucheru-Muna M, & Muriu-Ng'ang'a F (2023). Zai pit combined with integrated nutrient management for improving soil aggregate stability, moisture content and microbial biomass in drylands of Eastern Kenya, African Journal of Agricultural Research, 19(9): 904-922. https://doi.org/10.5897/AJAR2022.16238

Kilasara M, Boa ME, Swai EY, Sibuga KP, Massawe BHJ, & Kisetu E (2015). Effect of In Situ Soil Water Harvesting Techniques and Local Plant Nutrient Sources on Grain Yield of Drought-Resistant Sorghum Varieties in Semi-arid Zone, Tanzania. Springer International Publishing, 13, 255-271.

Kimaru SW (2017). *Zai pits* and integrated soil fertility management enhances crop yields in the drier parts of Tharaka Nithi county, Kenya. PhD thesis. Kenyatta University, Kenya.

Kimaru-Muchai SW, Ngetich FK, Mucheru-Muna MW, & Baaru M (2021). Zai pits for heightened sorghum production in drier parts of Upper Eastern Kenya. *Heliyon*, 7: https://doi.org/10.1016/j.heliyon.2021.e08005

Kubiku FNM, Mandumbu R, Nyamadzawo G, & Nyamangara J (2022b). Field edge rainwater harvesting and inorganic fertilisers for improved sorghum (*Sorghum bicolor L*.) yields in semi-arid farming regions of Marange, Zimbabwe. *Heliyon*, 8. https://doi.org/10.1016/j.heliyon.2022.e08859

Kubiku FNM, Nyamadzawo G, Nyamangara J, & Mandumbu R (2022a). Effect of contour rainwater harvesting and integrated nutrient management on sorghum yield in semi-arid farming environments of Zimbabwe. *Acta Agriculturae Scandnavica Section B-Soil* & *Plant* Science, 72 (1):364-374 https://doi.org/10.1080/09064710.2021.2005130

Kugedera AT, Mandumbu R, & Nyamadzawo G (2022b) Rainwater harvesting and *Leucaena leucocephala* biomass rates effects on soil moisture, water use efficiency and *Sorghum bicolor* [(L.) Moench] productivity in a semi-arid area in Zimbabwe. Journal of the Science of Food and Agriculture, 102 (14): 6443-6453. https://doi.org/10.1002/jsfa.12011

Kugedera AT, Mandumbu R, & Nyamadzawo G (2023a) Compatibility of *Leucaena leucocephala* biomass and cattle manure combination under rainwater harvesting on sorghum (*Sorghum bicolor* (L.) Moench) productivity in semi-arid region of Zimbabwe. Journal of Plant Nutrition, 46 (8): 1580-1600. https://doi.org/10.1080/01904167.2022.2092512

Kugedera AT, Nyamadzawo G, & Mandumbu R (2022c) Augmenting *Leucaena leucocephala* biomass with mineral fertiliser on rainwater use efficiency, agronomic efficiency and yields on sorghum (*Sorghum bicolor* [(L.) Moench]) under rainwater harvesting techniques in semi-arid region of Zimbabwe. Heliyon, 8(7) e09826. https://doi.org/10.1016/j.heliyon.2022.e09826

Kugedera AT & Kokerai LK (2019). Effects of In Situ Rainwater Harvesting and Cattle Manure to Improve Sorghum Yield. International Journal of Agriculture and Agribusiness. 2 (2), 243–248.

Kugedera AT & Kokerai LK (2024). A review on the effects of mineral fertiliser, manure and water management in improving sorghum grain yields in semi-arid areas. Journal of Plant Nutrition, 47 (7): 1175-1188. https://doi.org/10.1080/01904167.2023.2297955

Kugedera AT, Mango L, & Kokerai LK (2020). Effects of integrated nutrient management and tied ridges on maize productivity in dry regions of Zimbabwe. *Octa Jour. Biosci*, 8(1): 7-13

Kugedera AT, Nyamadzawo G, Mandumbu R, & Nyamangara J (2022a). Potential of field edge rainwater harvesting biomass transfer and integrated nutrient management in improving sorghum productivity in semi-arid regions: a review. Agroforestry Systems, 96(4): 909-924. https://doi.org/10.1007/s10457-022-00751-w

Kugedera AT, Sakadzo N, Kokerai LK & Ranganai N (2023b). Water Harvesting Technologies for Sustainable Crop Production in African Smallholder Farming Systems. In: Fanadzo, M., Dunjana, N., Mupambwa, H.A., Dube, E. (Eds) Towards Sustainable Food Production in Africa. Sustainability Sciences in Asia and Africa. Springer, Singapore, 171-183. https://doi.org/10.1007/978-981-99-2427-1_10

Kugedera AT, Sakadzo N, & Kokerai LK (2023c). Agroforestry technologies and mineral fertilisers Combinations for improved Soil Fertility and Crop Production in Semi-Arid Areas of Africa. In: Fanadzo, M., Dunjana, N., Mupambwa, H.A., Dube, E. (Eds) Towards Sustainable Food Production in Africa. Sustainability Sciences in Asia and Africa. Springer Nature Singapore, 85-94. https://doi.org/10.1007/978-981-99-2427-1_5

Mafongoya PL, Bationo A, Kihara J, & Waswa BS (2006). Appropriate technologies to replenish soil fertility in southern Africa. *Nutrient Cycling in Agroecosystems*, 76: 137-151.

Mahinda A, Funakawa S, Shinjo H, & Kilasara M (2018). Interactive effects of in situ rainwater harvesting techniques and fertilizer sources on mitigation of soil moisture stress for sorghum (*Sorghum bicolor* (L.) Moench) in dryland areas of Tanzania, *Soil Science and Plant Nutrition*, 64:6, 710-718. http://doi.org/10.1080/00380768.2018.1525573

Mahmood F, Khan I, Ashraf U, Shahzad T, Hussain S, Shahid M, Abid M, & Ullah S (2017). Effects of organic and inorganic manures on maize and their residual impact on soil physico-chemical properties. J. Soil Sci. Plant Nutr. 17: 22–32.

Maluki M, Mounde LG, Mwololo JK, & Gogo EO (2020). Integrated use of NPK fertilizer, cattle manure and management of leaf harvest frequency improves yield and economic returns of butternut. Afr. J. Hort. Sci, 18:13-30.

Mamuye M, Nebiyu A, Elias E, & Berecha G (2021). Combined use of organic and Inorganic nutrient sources improved maize productivity and soil fertility in Southwestern Ethiopia. *International Journal of Plant Production*, https://doi.org/10.1007/s42106-021-00144-6

Mesfin T, Gebreyesus BT, Wortman C, Nikus O, & Mamo M 2009. Tied ridging and fertilizer use for sorghum production in semi-arid Ethiopia. Nutr Cycl Agrosyst. 85, 87-94. http://doi.org/10.1007/s10705-009-9250-2

Motsi KE, Chuma E, & Mukamuri BB (2004). Rainwater harvesting for sustainable agriculture in communal lands of Zimbabwe. Phys. Chem. Earth, Parts A/B/C 29, 1069–1073. https://doi.org/10.1016/j.pce.2004.08.008

Muchai SWK, Ngetich FK, Baaru M, & Mucheru-Muna MW (2020). Adoption and utilisation of Zai pits for improved farm productivity in drier upper Eastern KenyaJ. Agr. Rural Develop. Trop. Subtrop. 121 (1):13–22. http://doi.org/10.17170/kobra-202002281030

Mucheru-Muna M, Mugendi D, Kung'u J, Mugwe J, & Bationo A (2007). Effects of organic and mineral fertilizer inputs on maize yield and soil chemical properties in a maize cropping system in Meru South District, Kenya. *Agroforestry Syst*, 69, 189-197: http://doi.org/10.1007/s10457-006-9027-4

Mucheru-Muna M, Mugendi D, Pypers P, Mugwe J, Kung'u J, Vanlauwe B, & Merckx R (2014). Enhancing maize productivity and profitability using organic inputs and mineral fertilizer in central Kenya small-hold farms. Exp. Agric. 50, 250–269. https://doi.org/10.1017/S0014479713000525.

Mugendi DN, Kanyi M, Kungu JB, Wamicha W, & Mugwe JN (2003). The role of agroforestry trees in intercepting leached nitrogen in the agricultural systems of the central highlands of Kenya. *East African Agricultural and Forestry Journal*, 69:69-79.

Mugwe J, Mugendi D, Kungu J, & Mucheru-Muna M (2009a). Maize yields response to application of organic and inorganic input under on-station and on-farm experiments in Central Kenya, *Experimental Agriculture*. 45 47–59. http://doi:10.1111/j.1475-2743.2009.00244.x

Mugwe J, Mugendi D, Mucheru-Muna M, Odee D, & Mairura F (2009b). Effect of selected organic materials and inorganic fertilizer on the soil fertility of a *Humic nitisol* in the central highlands of Kenya. *Soil Use and Management*, 25, 434-440. https://doi.org/10.1111/j.1475-2743.2009.00244.x.

https://doi/org/10.57046/HRBT3684

Mugwe JN (2007). An evaluation of integrated soil fertility management practices in Meru south district, Kenya. DPhil thesis, Kenyatta University.

Mugwe JN, Ngetich F, & Otieno EO (2019). Integrated Soil Fertility Management in Sub-Saharan Africa: Evolving Paradigms toward Integration. *Springer Nature Switzerland AG*: 1-13. https://doi.org/10.1007/978-3-319-69626-3_71-1

Mugwe JN & Otieno EO (2021). Integrated Soil Fertility Management Approaches for Climate Change Adaptation, Mitigation, and Enhanced Crop Productivity, In W. Leal Filho et at. (eds), Handbook of Climate Change Management, Springer Nature Switzerland AG. https://doi.org/10.1007/978-3-030-22759-3_325-1

Mugwe JN, Mugendi D, Kungu JB, & Mucheru-Muna M (2007). Effects of plant biomass, manure and inorganic fertilizer on maize yield in the central highlands of Kenya. *African Crop Science Journal*, 15(3): 111-126.

Mwadalu R, Mochoge B, Mwangi M, Maitra S, & Gitari H (2022). Response of Gadam Sorghum (*Sorghum bicolor*) to farmyard manure and inorganic fertiliser application. International Journal of Agriculture, Environment and Biotechnology, 15 (01): 51-60. https://doi.or/10.30954/0974-1712.01.2022.6

Mwende N, Danga B, Mugwe J, & Kwena K (2019) Effects of integrated Tied ridging, Fertiliser and cropping systems on Maize performance in arid and semi-arid lands of Eastern Kenya. *African Journal of Education, Science and Technology*, 5(2):87-91

Ndung'u M, Mugwe JN, Mucheru-Muna MW, Ngetich FK, Mairura FS, & Mugendi DN (2023). Tied ridging and soil inputs enhance small-scale maize productivity and profitability under erratic rainfall conditions in central Kenya. Agricultural Water Management, 286 (2023) 108390. https://doi.org/10.1016/j.agwat.2023.108390

Nyagumbo I, Nyamadzawo G, & Madembo C (2019). Effects of three in-field water harvesting technologies on soil water content and maize yields in a semi-arid region of Zimbabwe. Agricultural Water Management, 216, 206–213. http://doi.org/10.1016/j.agwat.2019.02.023

Nyakudya IW, Stroosnijder L, & Nyagumbo I (2014). Infiltration and planting pits for improved water management and maize yield in semi-arid Zimbabwe. Agricultural Water management 141, 30-46. http://dx.doi.org/10.1016/j.agwat.2014.04.010

Nyamadzawo G, Gotosa J, Govere I, & Mabodo I (2015). The Potential of Tied Contours for In-field Water Harvesting on Maize Yields in Semi-arid Marange Smallholder Farming. Working Paper.

Nyamangara J, Mudhara M, & Giller KE (2005). Effectiveness of cattle manure and nitrogen fertiliser application on the agronomic and economic performance of maize. *South African Journal on Plant & soil*, 22 (1),59-63. https://doi.org/10.1080/02571862.2005.10634682

Odour NO (2022). Integrated soil fertility and water management practices for enhanced sorghum (*Sorghum bicolor*) productivity in the drylands of Tharaka-Nithi County, Kenya. PhD thesis,

https://doi/org/10.57046/HRBT3684

University of Embu, Kenya.

Oduor NO, Mucheru-Muna M, Mugwe JN, Sijali I, Nyabuga G, & Mugendi DN (2023). Soil water use efficiency under integrated soil management practices in the drylands of Kenya. Heliyon, 9:e16145. https://doi.org/10.1016/j.heliyon.2023.e16145

Sebnie W, Mengesha M, Girmay G, Feyisa T, Asgedom E, Beza G, & Dejene D (2020). Evaluation of micro-dosing fertilizer application on sorghum (*Sorghum bicholor* L) production at Wag-Lasta Areas of Amhara Region, Ethiopia. Scientific Reports 10, 6889. https://doi.org/10.1038/s41598-020-63851-6

Sebnie W, Mengesha M, Girmay G, Feyisa T, Asgedom E, Beza G, & Dejene D (2020). Evaluation of micro-dosing fertilizer application on sorghum (*Sorghum bicholor* L) production at Wag-Lasta Areas of Amhara Region, Ethiopia. Scientific Reports, 10:6889. https://doi.org/10.1038/s41598-020-63851-6

Sher A, Adnan M, Sattar A, Ul-Allah S, Ijaz M, Hassan MU, Manaf A, Qayyum A, Elesawy BH, Ismail KA, Gharib AF, & Askary AE (2022). Combined Application of Organic and Inorganic Amendments Improved the Yield and Nutritional Quality of Forage Sorghum. Agronomy, 12, 896. https://doi.org/10.3390/agronomy12040896

Sileshi GW, Jama B, Vanlauwe B, Negassa W, Harawa R, Kiwia A, & Kimani D (2019). Nutrient use efficiency and crop yield response to the combined application of cattle manure and inorganic fertilizer in sub-Saharan Africa. Nutrient Cycling in Agroecosystems, 113:181–199. https://doi.org/10.1007/s10705-019-09974-3

Swai EY, Mwinuka L, Shitindi MJ, Manda J, Whitebread A, & Bekunda M (2023). Factoring labour when comparing *in situ* rainwater harvesting technologies for semi-arid areas of central Tanzania, Archives of Agronomy and Soil Sciences. https://doi.org/10.1080/03650340.2023.2175352

Tapiwa AK, Lawrence M, & Kudzai KL (2020). Evaluating the effects of integrated nutrient management and insitu rainwater harvesting on maize production in dry regions of Zimbabwe. International Journal of Agriculture Environment and Food Science, 4(3), 303-310. https://doi.org/10.31015/jaefs.2020.3.9.

Tsujimoto Y, Tanaka A, & Rakotoson T (2021). Sequential micro-dose fertilization strategies for rice production: Improved fertilizer use efficiencies and yields on P-deficient lowlands in the tropical highlands. European Journal of Agronomy, 131:1-9. https://doi.org/10.1016/j.eja.2021.126381

Wang L, Leghari SJ, Wu J, Wang N, Pang M, & Jin L (2023) Interactive effects of biochar and chemical fertilizer on water and nitrogen dynamics, soil properties and maize yield under different irrigation methods. Front. Plant Sci. 14:1230023. https://doi.org/10.3389/fpls.2023.1230023

Workineh E, Yihenew GS, & Eyasu E (2022). Integrated use of compost and lime enhances soil properties and wheat (*Triticum aestivum* L.) yield in acidic soils of Northwestern Ethiopia. International Journal of Recycling of Organic Waste in Agriculture,

https://doi/org/10.57046/HRBT3684

https://doi.org/10.30486/IJROWA.2022.1941048.1343

Xia H, Riaz M, Zhang M, Liu B, El-Desouki Z, & Jiang C (2020). Biochar increases nitrogen use efficiency of maize by relieving aluminium toxicity and improving soil quality in acidic soil. Ecotoxicol. Environ. Saf. 196, 110531. https://doi.org/10.1016/j.ecoenv.2020.110531