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Irrigation-nutrition linkages under farmer-led and public irrigation schemes in Kenya

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Abstract

Though the suggested pathways of achieving nutrition through irrigation are production, income, water sanitation and hygiene and women's empowerment, the linkages to nutritional outcomes are not understood well and often, nutritional measurement approaches neglect the households' most vulnerable members; women and children. This study took the standpoint that irrigation is diverse and different irrigation arrangements (i.e. socio-technical set-ups in which irrigation takes place) affect household nutritional outcomes through different pathways. Using a simultaneous equation model and data from Kenya, the results showed that the different irrigation arrangements have different nutrition-outcome pathways. The results revealed that overall irrigation affects production diversity, farm income and women empowerment and nutrition-outcomes were improved through production diversity and income pathways. The farm households in the public irrigation scheme arrangements attained better nutritional outcomes only through the women empowerment pathway while it affected production diversity pathway negatively. The farmer-led irrigation arrangement was found to positively affect farm income and women empowerment and these two pathways were found to lead to improved household nutritional outcomes. Consequently, there is need for specific policy interventions based on irrigation arrangements as opposed to a unilateral policy encompassing irrigation.

Keywords: agriculture-nutrition pathways; irrigation institutions; three-stage least squares (3SLS) estimation; Kenya; Sub-Saharan Africa

JEL Codes: Q000; Q190; Q100

1. Introduction

Under the auspices of war in Ukraine and the Covid-19 crisis, the world is backtracking on its food and nutrition security achievements in the last decade. While under the Millennium Development Goals the undernourished population was poised to reduce from approximately 23% in the early 1990s to about 13% by the end of 2015 (United Nations, 2015), the proportion of people facing moderate to severe food insecurity stands at almost 30% which is higher than the pre-pandemic levels in 2019 (FAO, IFAD, UNICEF, WFP, WHO, 2023). The combined negative effect of the war in Ukraine and the Covid-19 pandemic is projected to lender over 100 million people undernourished by the year 2030 (FAO, IFAD, UNICEF, WFP, WHO, 2023; Kornher & von Braun, 2023; F. Lin et al., 2023; Rahut et al., 2022).

On the other hand, extreme climatic events continue to pose a great risk to achieving the much needed increase in agricultural production to feed a growing population that is estimated to reach over nine billion by mid this century (De Wrachien et al., 2021). Among the key issues of concerns include the rising temperatures whose adverse effects on agricultural production is already evident and is projected to increase (Liu et al., 2023; D. Wang et al., 2023; Zhu et al., 2022). In addition, the recent data shows that from the year 2010, deaths due to extreme weather events such as storms, droughts and floods has increases 15 times posing a greater risk in the coming years to over the 3 billion people who live in areas vulnerable to climatic change related disasters (IPCC, 2023).

Under these challenges, increasing agricultural production as well as galvanizing the current production against weather and climatic risks has become a crucial global target. In this context, irrigation has been proposed as one of the ways through which the global agricultural production can be bolstered while overcoming climatic ricks and challenges. This is due to the unique opportunities that irrigation presents such as increasing production (De Wrachien et al., 2021; Mueller et al., 2012; Sauer et al., 2010; X. Wang et al., 2021; Wichelns & Oster, 2006), utilizing marginal and water-stressed lands (Altchenko & Villholth, 2015; Shahid & Al-Shankiti, 2013; L. Wang et al., 2022) and safeguarding agriculture from climatic and weather risks (Agathokleous et al., 2023; BenYishay et al., 2023; Rosa et al., 2020a; L. Wang et al., 2022).

One of the regions that can benefit immensely from irrigation development is sub-Saharan Africa (SSA). SSA currently has the highest absolute prevalence of undernourishment globally. About 67% of SSA population are moderately or severely food insecure while approximately 6% of the children under five years suffers from wasting and prevalence of anemia in women of productive age is at about 41% (FAO, IFAD, UNICEF, WFP, WHO, 2023; FAO, 2023).

While irrigation has been proven to increase agricultural production and positively impact food and nutrition security (Kafle et al., 2020), irrigation development is low in SSA. Irrigation only covers about 6% of the area under cultivation in SSA and estimates show that only about 1% of the region's irrigation potential is utilized (Durga et al., 2024; van Maanen et al., 2022; You et al., 2011). One of the reasons for this low development has been a focus on irrigation schemes that require substantial investments (Durga et al., 2024). Irrigation schemes are mostly public (often with development partners' support) funded comprising of costly irrigation infrastructure. In addition to this unilateral challenges, obstacles such as financial limitations to undertake these costly irrigation investment (Kafle et al., 2020; Wazed et al., 2018; Xie et al., 2021) and the absence or unclear policy and institutional support frameworks (Chokkakula & Giordano, 2013; Closas & Rap, 2017; Hjalmarsdottir, 2012) hinder the growth of irrigation development in SSA. This single-mindedness on irrigation schemes in Africa has led to the disregard of irrigation development that is farmer instigated, owned and driven that has been expanding despite little policy recognition and the challenges to irrigation development in SSA mentioned. This type of irrigation arrangement has been termed as farmer-led irrigation development (FLID).The World Bank describes farmer-led irrigation as "when farmers drive the establishment, improvement, and/or expansion of irrigated agriculture and influence the location, purpose, and design of irrigation development through small-scale, on-farm, locally relevant, and market-oriented solutions" (World Bank, 2021). In this study, irrigation is separated in these two distinct institutional set ups of public irrigation scheme arrangements and farmer-led irrigation arrangements and investigation on irrigation-nutrition pathways was done using data from rural Kenya.

2. Statement of the problem

While Kenya is one of SSA's economic powerhouses, the country's food and nutrition security is still wanting. While nationally about 25% of the population is undernourished, some areas in the semi-arid and arid regions of the country have a prevalence rate of about 70% (FAO, IFAD, UNICEF, WFP, WHO, 2023). Approximately 18% of the children under five years suffer from stunting and about 5% from wasting while about 29% of the women of productive age are anemic (FAO, 2023, 2023; World Bank, 2023). Therefore, increasing agricultural production and attaining nutrition security is a key priority for the country.

Kenya's agricultural production faces climatic challenges given that over 80% of the country's land area is unsuitable for rain-fed agriculture (Hornum & Bolwig, 2020; Njoka et al., 2016). Additionally, it's geographical location in the horn of Africa has made the country vulnerable to negative effects of climate change that has made drought cycles frequent with the one experienced recently being between the year 2021 and 2023 which was the worst drought in 4 decades (Gebre et al., 2023; Marigi, 2017 ;Devi, 2023; Leal Filho et al., 2023; Salm-Reifferscheidt, 2023). This makes irrigation development a key focus of the government's policy given that the country has huge unexploited irrigation potential with merely 19% of surface water and drainage irrigation developed (National Irrigation Authority, 2019). However, despite this immense irrigation potential, the type of irrigation development to undertake has been a debate in Kenya as well as in SSA (Lankford, 2009; Woodhouse et al., 2017), especially after the failure of irrigation schemes investments in the last decades of the last century (Woodhouse et al., 2017). This has seen the policy arena embark on looking at other viable irrigation arrangements such as FLID.

However, while research shows clear interlink between water infrastructure and the users that give rise to different sociotechnical situations in irrigation (Kloezen & Mollinga, 1992; Mollinga, 1998; Narain & Singh, 2017; Uphoff, 1986, pp. 1–2), this has unfortunately been overlooked in research and policy arenas. As such, irrigation has been studied, evaluated and analyzed as a single input factor disregarding the different sociotechnical conditions that arise due to social construction around water infrastructures (Mollinga, 2003; Van der Kooij et al., 2015). In this study, the different sociotechnical settings of irrigation water use are referred to as irrigation arrangements.

However, the linkages between agriculture and nutrition remain understudied, empirical evidence is scarce and when available it is weak (Ruel et al., 2018; Webb & Kennedy, 2014). The inadequate empirical evidence in agriculture-nutrition research has been attributed to weak study designs that yield non-generalizable results that render nutritional effects hidden (Domènech, 2015; Jaenicke & Virchow, 2013; Webb & Kennedy, 2014).

Similarly, the pathways through which irrigation impacts on nutritional outcomes are understudied, with only few rigorous studies available (Domènech, 2015; Hanjra & Williams, 2020). This underscores the need for a comprehensive investigation on the linkages between irrigation and nutrition in a manner that takes into account various socio-technical irrigation arrangements and their differential effects on nutrition outcomes.

Moreover, despite irrigation's contribution to agricultural production, irrigation and nutrition linkages are ambiguously understood (Ringler et al., 2018) with much of the focus of irrigation development being on grain production that leans towards caloric increase and neglects holistic nutritional aspects (Fan & Pandya-Lorch, 2012, p. 2; Gillespie & van den Bold, 2017; Hawkes & Ruel, 2012, pp. 75–76). In Kenya, irrigation development is mostly focused on caloric-rich grains and export high value crops with very little of it being used for nutrition-dense crops such as vegetables for the local population (Hornum & Bolwig, 2020; Mati, 2008). Therefore, as the country endeavors to expand its irrigated agriculture, there is a pressing need to focus on how it can lead to improved nutritional outcomes (Muthayya et al., 2013; Ruel et al., 2018).

While the crucial role socioeconomic factors play have been widely acknowledged in economic disciplines, studies that look into their role in irrigation and particularly expansion of irrigation has been largely understudied (Hatch et al., 2022; Kamwamba-Mtethiwa et al., 2016; van Maanen et al., 2022). With most of the socioeconomic factors being uniquely localized with some affected by socio-cultural practices, it is imperative for studies to take socioeconomic factors in account while evaluating irrigation arrangements. This has been particularly come as a matter of importance due to the climate change challenges and the inevitable need for expanding irrigated agriculture, that has led a call for need for including socioeconomic factors in research works in a bid to better direct future irrigation investments (Rosa et al., 2020b; van Maanen et al., 2022). This research thus focusses on contributing to this policy debate especially in the socioeconomic factors effect on the irrigation-nutrition pathways. This study thus undertook to investigate the irrigation-nutrition pathways for different irrigation arrangements for smallholder farm households in rural Kenya while controlling for the different socioeconomic factors inherent in each smallholder farm household.

3. Conceptual framework

In this study, irrigation is taken as a form of agricultural production at the household level and seeks to show its linkages to nutritional outcomes. The conceptual framework developed by (Herforth & Harris, 2014) is used in linking agriculture to nutritional outcomes. To do this we adapt the methodology by (Passarelli et al., 2018) where irrigation is a production innovation for the smallholder households to achieve their nutritional outcomes through the food production, agricultural income, and women's empowerment pathways as suggested by Domenech & Ringler (2013). By taking irrigation as an agricultural innovation component, the distinguishing of irrigating and non-irrigating households and the different irrigation arrangements is thus made possible. The resulting conceptual framework is presented in Figure 1.

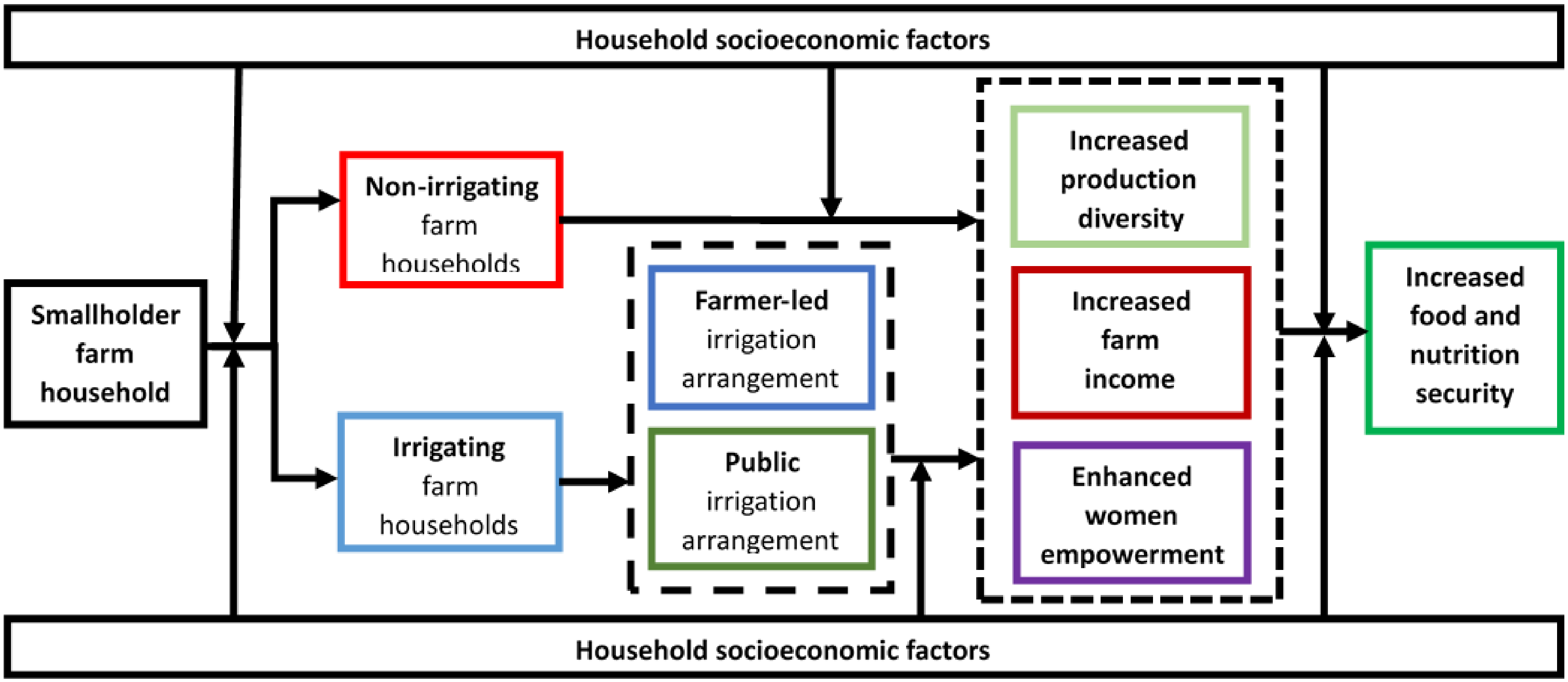

Figure 1: Conceptual framework for the Pathways from irrigation to nutrition.
Source: Authors' own conceptualization. Pathways adapted from Herforth & Harris (2014) and Domènech (2015).

4. Methodology

4.1. Study area and sampling

This research was done in the Mwea Irrigation Scheme which is Kenya's oldest public irrigation scheme. Due to the availability of the water primarily for the irrigation scheme, the area has also developed as an agricultural region with farmer-led irrigation being common in the area (Momanyi et al., 2019; Tomizuka et al., 2019). This existence of different irrigation arrangements (public and farmer-led), made the area ideal for the study.

With the information gathered from the pilot survey, key informant interviews and the focus group discussions, the area was split into three semi-circular strata. The strata were based on the distance from the Nyamindi river that also has the headway to the main one of the headway of the main canal. In addition, the area East of Nyamindi acted as the boundary to the semi-circles with the area removed from the sample as discussed earlier. This was deemed necessary so as to have a good distribution of farmers in both the public scheme irrigation arrangement, farmer-led irrigation arrangement and non-irrigators. This method was deemed fit over a simple random sampling in getting the precision needed to have a sufficient sample in these different irrigation arrangements that allows for comparative analysis as illustrated in (Deaton, 2019, p. 13).

However, with water resources being a key factor in irrigation (or rather the basic substance), following the basin of these rivers or the subsequent canals in the irrigation system would produce a biased sample. In this respect, the administrative subdivisions consisting of Sub-Counties, Locations and sub-locations in these three stratified areas based on distance were chosen in random. From a list of seventeen locations derived from the Sub-County Commissioner, fourteen were chosen randomly in the stated semi-spherical stratified areas. In these Locations, there was a total of thirty-seven Sub-Locations from which twenty-seven Sub-Locations were randomly chosen.

At the Sub-Location, households from seventy-five villages were chosen randomly. However, at the village level, there lacked a list of all households in a village. As such the study used a list of existing security grouping of ten households referred to as "nyumba kumi" which is a Community Policing strategy that primarily works at household level (Brown et al., 2016; National Police

Service, 2017; Ndono et al., 2019). In each village, farmers were chosen in their groupings randomly with replacement if the chosen household was not available. Having the key variables of clustering these households as security reasons based on physical proximity made these grouping ideal for sampling as they are not in any way related to farming practices especially irrigation and also were representative of the community. In addition, with the households in the villages not having a distinct home address, these groupings provided a much needed list for random sampling. Therefore, one household was picked from each of the ten household groupings in the village selected. Households were sampled regardless of their irrigation arrangement with the classification of the arrangements left to the researcher as opposed to the enumerators.

Following the work by Cochran (2007) and Israel (1992) three critical factors were considered in calculating the sample size of this study; level of precision, confidence level and degree of variability. Therefore, with the three key criteria deemed important for the research, the study adopted the sampling formula by Cochran (1963) to get the appropriate sample size for the study. The formula is defined as:

$$n_0 = \frac{Z^2 pq}{e^2}$$

Equation 1

Where n_0 is the total sample size, Z is the z-value from the Z table and represents the area under a normal curve, p is the approximated proportion with the desired attribute, q is equal to 1-p and e is the margin of error or the desired precision level. Since we do not know the proportion of households in this area the two irrigation arrangements and non-irrigators the study assumed the maximum level of variability of 50%. The normally recommended level of confidence of 95% was adopted and a precision level of 5%. This then gave a total sample size of 384 smallholder farm households.

4.2. Econometric modelling

The three-stage least squares (3SLS) estimation method followed the analytical framework of Zellner and Theil (1962). The irrigation and irrigation arrangements equation is defined in the binary nature where the factors that influence the irrigation and the different irrigation arrangements. The irrigation equation was defined as:

$$I_h = \alpha_I + \beta^I_{hsc} X_{hsc} + \mu^I_h$$

Equation 2

Where I_h is the irrigation status of household h, α_I is a constant to be estimated, β^I_{hsc} is the parameter to be estimated of the household's socioeconomic factors that affect irrigation and irrigation arrangements, $X_{hsc}$is the household's socioeconomic factors and μ^I_h is the error term where μ^I_h ~ N(0,1). The Equation 2 above is included in the production diversity, income and women's empowerment equations.

Production diversity score is defined same category for dietary diversity. This was informed by research that shows that a measurement of the production diversity and dietary diversity under the same food grouping gives better plausible analysis especially for rural subsistence farm households that primarily consumes food produced in the farms (Berti, 2015; Sibhatu et al., 2015b). In this study it is postulated that irrigation can enable a household to grow more diverse foods and thus enable it to access more diverse and nutritious food (Alaofè et al., 2016; Domènech, 2015; LaFevor & Pitts, 2022) and also smoothen production over dry seasons thus giving them access to nutritious foods. The production diversity equation is defined as shown below:

$$PD_h = \alpha_{PD} + I_h + \beta^{PD}_{hsc} X_{hsc} + \mu^{I,PD}_h$$

Equation 3

Where PD_h is the household's production diversity score defined as under the same categories as the MDD-W (informed by research that associating the diet of a household to its production, a measurement of the production diversity and dietary diversity under the same food grouping gives better plausible analysis especially for rural subsistence farm households that primarily consumes food produced in the farms (Berti, 2015; Sibhatu et al., 2015b)), α_{PD} is a constant to be estimated, I_h is the irrigation status and irrigation arrangement of the household as defined in Equation 2, β_{hsc}^{PD} is the parameter to be estimated of the household's socioeconomic factors that affect irrigation and irrigation arrangements, $X_{hsc}$is the household's socioeconomic factors and $\mu_h^{I,PD}$ is the normally distributed error term where μ ~ N(0,1).

Postulating that irrigation increases the household's farm income (Bhattarai et al., 2001; Hussain & Wijerathna, 2004; Li et al., 2020), farm income is also included in this study as a pathway to increasing nutritional outcomes of households. Though not linear (SPRING, 2014a) (hence the use of this simultaneous equation modelling approach), it is anticipated that this enables the household to have more disposable income to access nutritious foods (Rao & Pingali, 2018). This includes more expensive nutrient rich foods such as protein foods. The income equation was thus specified as:

$$Finc_h = \alpha_{Finc} + I_h + \beta_{hsc}^{Finc} X_{hsc} + \mu_h^{I,PD,Finc}$$

Equation 4

Where $Finc_h$ is the household's farm income, α_{Finc} is a constant to be estimated, I_h is the irrigation status and irrigation arrangement of the household indicating whether they irrigate or not or the irrigation arrangement, β_{hsc}^{Finc} is the parameter to be estimated of the household's socioeconomic factors that affect irrigation and irrigation arrangements, $X_{hsc}$is the household's socioeconomic factors and $\mu_h^{I,PD,Finc}$ is the error term with a mean of zero and a standard deviation of one.

The women's empowerment was measured using the Abbreviated women's empowerment in agriculture index (A-WEAI) (Alkire et al., 2013; H. Malapit et al., 2015; H. J. Malapit et al., 2017) There exists quite substantial evidence that women's empowerment in linked to nutritional outcomes, though a quite debate-arousing area (Bold et al., 2013; SPRING, 2014b; Heckert et al., 2019; Quisumbing et al., 2021; Santoso et al., 2019). This study thus predicted that irrigation does influence women's empowerment and women's empowerment in turn affects nutrition. The women's empowerment equation was specified as:

$$WE_h = \alpha_{WE} + I_h + \beta_{hsc}^{WE} X_{hsc} + \mu_h^{I,PD,Finc,WE}$$

Equation 5

Where WE_h is the A-WEAI of the primary woman decision maker, α_{WE} is a constant to be estimated, I_h is the irrigation status and irrigation arrangement of the household defined as above, β_{hsc}^{WE} is the parameter to be estimated of the household's socioeconomic factors that affect irrigation and irrigation arrangements, $X_{hsc}$is the household's socioeconomic factors and μ_h^{WE} is the error term.

The final structural equation in this simultaneous equation model is the dietary diversity score. The dietary diversity score was used as the proxy for nutrition. The score is measured using the minimum women dietary diversity (MDD-W) which categorizes the food eaten within a 24 hour period into ten food groups eaten (FAO & FHI 360, 2016; Kennedy & Ballard, 2011). This specific score was chosen since it is a stricter measure that takes into consideration the nutrients intake (FAO, 2021). Thus this involved taking the intake of the female household members of productive age. For triangulation, the data was collected on two different days and an average of the score taken. This formed the principle equation of the simultaneous equation model. It encompasses all the above equations and it was estimated using three-stage least squares approach (Zellner & Theil, 1962). This equation consisted of the dependent variables in equations Equation 2, Equation 3 and Equation 4. However, Equation 2 on irrigation was excluded in this equation. As such, the MDD-W equation which was a proxy of the nutritional outcome was specified as:

$$MDDW_h = \alpha_{MDDW} + PD_h + Finc_h + WE_h + I_h + \beta_{hsc}^{MDDW} X_{hsc} + \mu_h^{I,PD,Finc,WE,MDDW}$$

Equation 6

Where $MDDW_h$ is the A-WEAI of the primary woman decision maker, α_{MDDW} is a constant to be estimated, PD_h is the production diversity score as defined in Equation 3, $Finc_h$is the farm income as defined in Equation 4, $WE_h$is the women's empowerment as defined in Equation 5,

β_{hsc}^{MDDW} is the parameter to be estimated of the household's socioeconomic factors that affect irrigation and irrigation arrangements, X_{hsc} is the household's socioeconomic factors and μ_h^{MDDW} is the error term.

In this three-stage least squares (3SLS) model, for irrigation to influence the MDD-W, then it has to influence production diversity, farm income and women's empowerment. Additionally, production diversity, farm income and women's empowerment has to affect the MDD-W. In this manner, use of instrumental variables helps in solving for any endogeneity in these five structural equations. Furthermore, by using a simultaneous equation approach, the model is able to leverage on the efficiency gains as the error terms will most possibly be correlated in these five structural equations as shown in the equations above (see the connotations on the error terms). By doing this, the 3SLS model handle all the exogenous variables as instruments for any variable in which endogeneity exists.

4.3. Model validity

Two tests were applied to determine how effective the variables used in the simultaneous equation model. This is the Sargan–Hansen (Hansen, 1982; Sargan, 1958) and the Basmann (Basmann, 1960) tests of overidentification restrictions. To do this, we run a two stage simultaneous equation where we did assume that the four variables are endogenous to the dietary diversity. The tests' null hypothesis is that the model is overidentified.

The results of these tests showed that the model was just-identified with both the Sargan–Hansen and Basmann tests p-values not being significant. As such we fail to accept the null hypothesis that the irrigation, farmer-led irrigation arrangement and public irrigation scheme arrangement equations are overidentified.

5. Results and discussion

5.1. Descriptive statistics

The results indicate a difference between the public irrigation scheme- and farmer-led- irrigators and non-irrigators in terms of socioeconomic characteristic. Tests for statistical significance in the means was done by comparing the two irrigation arrangements and the non-irrigating farm households. The farmer-led irrigation arrangement has a higher value of household assets and membership to community groups as compared to the non-irrigating households. Household heads and the primary female decision-makers of the farmer-led and public irrigation scheme arrangements were younger as compared to the non-irrigators and a significantly higher level of education as well. Farm households in the public irrigation scheme arrangement had a lower livestock ownership but a higher access to in-kind credit as compared to non-irrigators.

Both the public irrigation scheme- and farmer-led irrigation- arrangements had a higher level of dietary diversity as compared to non-irrigating households. Remarkably, among the irrigators there are no observations for the dietary diversity below 3 but on the contrary some of the non-irrigator households show an MDD-W of 1 which indicates serious undernourishment.

For the three impact pathways, irrigating households in both arrangements has a significantly higher income as compared to the non-irrigators. While both irrigation arrangements had a lower production diversity than the non-irrigators, difference in production diversity was only statistically significant for households in the public irrigation scheme arrangement. While the level of empowerment was high above 0.73 and the farmer-led irrigation arrangement had the highest level of empowerment, the differences were not significant.

Table 1: Descriptive statistics of variables by irrigation

Variables	Non-irrigators (n =198)				Public irrigation arrangement (n =89)					Farmer-led irrigation arrangement (n =97)				
	mean	p50	min	max	mean	p50	min	max	Two-sample t test (equal variances)	mean	p50	min	max	Two-sample t test (equal variances)
MDD-W	4.46	4.46	1.00	7.00	4.72	4.83	3.00	7.50	-2.2195*	4.93	5.00	3.00	8.00	-4.1428***
Production diversity	3.88	4.00	0.00	8.00	2.94	3.00	1.00	7.00	4.9128***	3.62	4.00	1.00	9.00	1.3395
Farm income	746.60	184.81	0.00	22400.15	1908.31	947.77	0.00	26301.09	-3.6448***	2140.97	830.00	0.00	17028.21	-4.2754***
Women empowerment	0.73	0.73	0.00	1.00	0.71	0.73	0.00	1.00	0.9534	0.74	0.73	0.20	1.00	-0.2771
Age of the household head (years)	56.22	55.50	18.00	106.00	49.03	48.00	22.00	85.00	3.5365**	47.45	48.00	22.00	78.00	4.5206***
Age of the primary female decision maker (years)	51.88	51.88	10.00	96.00	44.29	43.00	15.00	80.00	3.6918***	41.62	42.90	13.00	68.00	5.2462***
Assets (USD)	779.97	262.78	0.00	22009.59	1582.15	400.34	11.17	77288.89	-1.2789	2670.62	639.61	9.31	47790.71	-3.309**
Single adult household type	0.27	0.00	0.00	1.00	0.21	0.00	0.00	1.00	0.9778	0.13	0.00	0.00	1.00	2.6088*
Education level of the household head (years)	7.34	7.50	0.00	16.00	8.43	8.00	0.00	15.00	-2.1563*	9.09	8.00	0.00	16.00	-3.8774***
Education level of the primary female decision maker (years)	6.32	7.00	0.00	15.00	8.52	8.00	0.00	15.00	-4.4945***	8.25	8.00	0.00	26.00	-4.1845***
Household size	3.43	3.00	1.00	8.00	3.58	4.00	1.00	8.00	-0.7452	3.69	4.00	1.00	8.00	-1.3371
Land owned (acres)	1.54	1.00	0.13	18.13	1.39	1.00	0.00	10.00	0.6436	1.75	1.13	0.00	6.00	-0.9337
Tropical livestock units	0.74	0.80	0.00	3.26	0.55	0.10	0.00	2.75	1.8891*	0.72	0.16	0.00	3.40	0.1657
Non-farm income (USD)	523.68	51.21	0.00	6703.29	454.75	77.27	0.00	3910.25	0.5565	668.46	0.00	0.00	14803.09	-0.851
In-kind credit	0.01	0.00	0.00	1.00	0.07	0.00	0.00	1.00	-3.2136**	0.01	0.00	0.00	1.00	-0.5156
Household credit access	0.19	0.00	0.00	1.00	0.19	0.00	0.00	1.00	-0.0828	0.27	0.00	0.00	1.00	-1.5997
Household group membership	0.74	1.00	0.00	1.00	0.84	1.00	0.00	1.00	-1.9676*	0.82	1.00	0.00	1.00	-1.6676*

Note: *P<0.01, P<0.05 and* P< 0.10 means significant at the 1%, 5% and 10% probability levels, respectively.

Source: Authors based on survey data.

5.2. Regression results

The results of the regressions for the aggregated irrigation is presented in Table 2, for farmer-led irrigation arrangement in Table 3 and for public irrigation scheme arrangement in Table 4. The structure and parameter for all the analyses was maintained for comparability purposes.

The results from the aggregated irrigation showed that irrigation significantly improved farm income and women's empowerment. These associations between irrigation farm income and women's empowerment were significant at 99% level of confidence. Sequentially, an improvement in the farm income and women's empowerment led to higher dietary diversity at the household level. The model showed the increase of dietary diversity due to farm income and women's empowerment was statistically significant at 95% level of confidence while for the women's empowerment it was at 99% level of confidence. On the other hand, irrigation influenced production diversity negatively. The statistical significance of the influence of irrigation on production diversity was also at 99% level of confidence. This means that while irrigation increases farm income and women's empowerment, it reduces production diversity at household level. However, the influence of production diversity on dietary diversity was found not to be statistically significant. This suggests that farm income and women's empowerment are the only viable ways through which irrigation influences household nutrition outcomes.

However, the bulwark claim of this research is that different irrigation arrangements affect production diversity, farm income and women's empowerment differently. In addition, I make a claim that the different irrigation arrangements have different irrigation-nutrition pathways. Therefore, the above result is used as a comparison to show the basis as to why disaggregated analysis in irrigation is necessary.

The analysis showed that being in the farmer-led irrigation arrangement leads to an increase in farm income and women's empowerment at household level. The statistical significance for the farm income and women's empowerment was at 99% and 90% level of confidence respectively. For the farmer-led irrigation arrangement analysis, this arrangement does not have a significant influence on production diversity.

Table 2: 3SLS results of a simultaneous system of minimum dietary diversity for women, household production diversity, farm income, women's empowerment and irrigation for the pooled samples

Variables	MDD-W	Production diversity	Log of farm income (USD)	Women's empowerment	Irrigation
Production diversity	-0.047				
	(0.079)				
Log of farm income (USD)	0.090**				
	(0.041)				
Women's empowerment	1.481***				
	(0.543)				
Household size	0.021		0.151**	-0.008	-0.01
	(0.033)		(0.074)	(0.006)	(0.013)
Employed†	-0.186				
	(0.12)				
Age of the household head (years)	-0.014**	0.004	0.003	0.000	0.001
	(0.007)	(0.011)	(0.015)	(0.001)	(0.003)
Age of the primary female decision maker (years)	0.009	-0.010	0.001	0.002**	-0.005*
	(0.007)	(0.011)	(0.015)	(0.001)	(0.003)
Tropical livestock units	0.255***	0.849***	0.257	-0.005	0.004
	(0.095)	(0.094)	(0.469)	(0.011)	(0.024)
Education level of the household head (years)	-0.008	0.012	0.096***	0.001	-0.009
	(0.016)	(0.024)	(0.037)	(0.003)	(0.006)
Education level of the primary female decision maker (years)	0.024	-0.017	-0.047	0.000	0.015**
	(0.017)	(0.026)	(0.047)	(0.003)	(0.007)
Distance to the market (Kilometers)	0.027*		-0.033	0.007**	-0.005
	(0.015)		(0.037)	(0.003)	(0.006)
Irrigation†		-0.859***	2.183***	0.134***	
		(0.204)	(0.402)	(0.034)	
Assets (USD)		0.000			0.000
		(0.000)			(0.000)
Single adult household type†		0.400**			
		(0.204)			
Primary female decision maker production decision†		0.085	-0.068	0.175***	-0.046
		(0.052)	(0.431)	(0.019)	(0.043)
Land owned (acres)		0.110***	0.277***	-0.001	-0.010
		(0.042)	(0.092)	(0.005)	(0.011)
Household group membership†		0.675(0.168)***			0.147***
					(0.042)
Production diversity			0.226		
			(0.637)		
Access to hybrid seed†			0.031	-0.005	0.103***
			(0.518)	(0.017)	(0.036)
Access to fertilizer†			1.644***	0.063*	0.099
			(0.632)	(0.033)	(0.072)
Land rental price (per acre)			0.000	<0.001***	0.002***
			(0.002)	(0.000)	(0.000)
Access to extra land†				-0.014	
				(0.021)	
Knowledge of pumping technology†					0.518***
					(0.041)
Single adult household type†					0.079
					(0.069)
Gender of the household head (Female)†					-0.012
					(0.068)
Constant	3.124***	2.651***	0.531	0.421***	0.050
	(0.427)	(0.495)	(1.854)	(0.061)	(0.138)
Parameters	11	11	14	14	17
Equation root mean squared error	0.895	1.355	1.933	0.158	0.341
Equation R-squared	0.045	0.255	0.341	0.141	0.534
Chi-square	58.440	154.830	180.240	124.190	457.220
Chi-square p-value	0.000	0.000	0.000	0.000	0.000
Number of observations	384	384	384	384	384

Note: Standard errors are listed below the coefficients in parentheses. † shows dummy variables. The notations and the meanings are as follows: *** p<.01, ** p<.05, and * p<.1.

Source: Authors based on survey data.

In similar fashion, there was no statistical significance for the households in farmer-led irrigation arrangement on the effect of production diversity on dietary diversity. This means that dietary diversity is not a pathway through which farmer-led irrigation arrangement households can achieve nutritional outcomes.

The farmer-led irrigation arrangement analysis showed that an improvement in the farm income and women's empowerment led to higher dietary diversity at the household level. The model showed the increase of dietary diversity due to farm income and women's empowerment was statistically significant at 99% and 90% level of confidence respectively. Therefore, this shows that the farmer-led irrigation arrangement households' irrigation-nutrition pathways are farm income and women's empowerment. As argued in the previous chapters, farmer-led irrigation arrangement is leans towards marketed products. Therefore, this may be the reason as to why the production diversity is not a significant nutrition pathway. Research has shown that production diversity might actually lead to a negative effect due to loss of income gained through specialization (Sibhatu et al., 2015a). In this case, it can be argued that the households choose not to have a diversified production due to the gains in specializing in market demanded products. This is beneficial to the household as farm income is an irrigation-nutritional pathway. In addition in such households, market access plays a more vital role in their nutritional outcomes and thus reduces production diversity's impact on the nutrition of the household as also argued by Sibhatu et al., (2015).

The effect of public irrigation scheme arrangement on production diversity, farm income and women's empowerment was similar to the results of the aggregated irrigation. Public irrigation scheme arrangement had a positive effect on farm income and women's empowerment and a negative influence on production diversity. However, the statistical significance for the effect of public irrigation scheme arrangement on women's empowerment was at 95% level of confidence while for farm income and women's empowerment was at 99% level of confidence. Therefore, being in the public irrigation scheme arrangement has the possibility to improve farm income and women's empowerment at household level but reduce the household's production diversity.

Table 3: 3SLS results of a simultaneous system of minimum dietary diversity for women, household production diversity, farm income, women's empowerment and irrigation for the farmer-led irrigation arrangement

Variables	MDD-W	Production diversity	Log of farm income (USD)	Women's empowerment	Irrigation
Production diversity	0.036				
	(0.099)				
Log of farm income (USD)	0.153***				
	(0.051)				
Women's empowerment	1.092*				
	(0.614)				
Household size	-0.008		0.119	-0.005	-0.017
	(0.038)		(0.091)	(0.006)	(0.012)
Employed	-0.256*				
	(0.143)				
Age of the household head (years)	-0.011	0.000	0.008	-0.001	0.001
	(0.008)	(0.012)	(0.018)	(0.001)	(0.002)
Age of the primary female decision maker (years)	0.008	0.000	-0.005	0.003**	-0.004*
	(0.008)	(0.012)	(0.019)	(0.001)	(0.002)
Tropical livestock units	0.083	0.826***	0.087	0.001	-0.032
	(0.111)	(0.106)	(0.429)	(0.012)	(0.021)
Education level of the household head (years)	-0.028	0.014	0.098**	0.001	-0.004
	(0.02)	(0.029)	(0.046)	(0.003)	(0.006)
Education level of the primary female decision maker (years)	0.039*	-0.023	-0.032	0.000	0.005
	(0.02)	(0.030)	(0.054)	(0.003)	(0.006)
Distance to the market (Kilometers)	0.022		-0.043	0.008***	-0.003
	(0.018)		(0.04)	(0.003)	(0.005)
Farmer-led irrigation arrangement		-0.214	2.009***	0.049*	
		(0.219)	(0.363)	(0.028)	
Assets (USD)		0.000			0.000
		(0.000)			(0.000)
Single adult household type		0.333			
		(0.230)			
Primary female decision maker production decision		0.112*	-0.122	0.167***	0.030
		(0.059)	(0.423)	(0.022)	(0.04)
Land owned (acres)		0.103**	0.218**	-0.002	-0.008
		(0.046)	(0.099)	(0.005)	(0.009)
Household group membership		0.720***			0.002
		(0.185)			(0.038)
Production diversity			0.558		
			(0.538)		
Access to hybrid seed			0.246	0.016	0.021
			(0.463)	(0.019)	(0.032)
Access to fertilizer			1.454**	0.070**	0.034
			(0.591)	(0.032)	(0.057)
Land rental price (per acre)			0.000	0.000	<0.001***
			(0.002)	(0.000)	(0.000)
Access to extra land				-0.018	
				(0.025)	
Knowledge of pumping technology					0.78***
					(0.036)
Single adult household type					0.035
					(0.062)
Gender of the household head (Female)					-0.075
					(0.062)
Constant	2.984***	2.129***	-0.292	0.403***	0.174
	(0.482)	(0.541)	(1.667)	(0.065)	(0.116)
Parameters	11	11	14	14	17
Equation root mean squared error	0.910	1.345	2.063	0.151	0.257
Equation R-squared	0.049	0.263	0.305	0.195	0.701
Chi-square	44.740	111.850	132.730	79.190	691.650
Chi-square p-value	0.000	0.000	0.000	0.000	0.000
Number of observations	295	295	295	295	295

Note: Standard errors are listed below the coefficients in parentheses. † shows dummy variables. The notations and the meanings are as follows: *** p<.01, ** p<.05, and * p<.1

Source: Authors based on survey data.

The reduction in production diversity in public irrigation scheme arrangement in turn does reduce dietary diversity. This negative effect of production diversity on dietary diversity was significant at 90% level of confidence. The results also showed that the positive effect of public irrigation scheme arrangement on farm income does not translate to an effect on dietary diversity. On the contrary, the positive effect on women's empowerment leads to an improvement in dietary diversity at a significance level at 90% level of confidence. Though negative, the significance of the effect of public irrigation scheme arrangement on production diversity and on dietary diversity does mean that production diversity is a practicable nutrition pathway. However, as concerns the status quo, women's empowerment is the only feasible way of the households in public irrigation scheme arrangement to improve their nutritional outcomes.

Furthermore, in the farmer-led irrigation arrangement analysis, the employment of a household member does reduce the dietary diversity of the household. This can be linked to the need for labor demand in farmer-led irrigation arrangement especially when rudimentary technologies such as fallow method are used that is labor intensive (Bjorneberg & Sojka, 2005; Friedman, 2023; Kloezen & Van Bentum, 1993). Therefore, employment draws away labor form the household that could be used in the farm. In addition, given that the results show that farm income and women's empowerment are the pathways through which these households in farmer-led irrigation arrangement achieve nutritional outcomes, then labor that either reduces production or burdens the other household members will in turn affect the household's nutrition.

The results showed that it affects dietary diversity in the aggregated irrigation analysis and public irrigation scheme arrangement analyses. This means that as the age of the household member increases, the household's dietary diversity reduces. After controlling for the effect of livestock ownership on production diversity, it was found that it increases dietary diversity in the aggregated irrigation and public irrigation scheme arrangement analyses. However, livestock ownership in the farmer-led irrigation arrangement did not have a statistically significant effect on dietary diversity. The positive association between livestock ownership and dietary diversity is in concurrence with other research (Bhagowalia et al., 2012; Flax et al., 2023; Jodlowski et al., 2016; Otte et al., 2012). The lack of effect of livestock ownership on dietary diversity for the households in the farmer-led irrigation arrangement can be partly explained by the non-significance of dietary diversity on production diversity. In the farmer-led irrigation arrangement case, livestock keeping leads to higher production diversity, production diversity does not have an effect on dietary diversity. As such, after controlling for the effect of livestock on production diversity in the model, the effect then is not significant on the dietary diversity. Moreover, in farmer-led irrigation arrangement analysis, after controlling for the effect of education level of the primary female decision maker on women's empowerment, it was found that it leads to a higher dietary diversity. This also is congruent to the pathway results as women's empowerment is a nutrition pathway for farmer-led irrigation arrangement households. This means that for farmer-led irrigation arrangement households, the more learned the primary female decision maker, the higher the women's empowerment and the higher the dietary diversity. Thus, the education level of the primary female decision maker has a direct effect on women's empowerment as well as dietary diversity for the farmers in the farmer-led irrigation arrangement.

In the aggregated analysis, the distance from the market influenced dietary diversity positively. This was after controlling for its effect on women's empowerment. On the other hand, the effect of the distance to the market on dietary diversity was not significant for the disaggregated analyses. The distance from the market was only significant in its effect on women's empowerment for the farmer-led irrigation arrangement analysis but this does not translate directly to an effect on dietary diversity but rather through women's empowerment.

Table 4: 3SLS results of a simultaneous system of minimum dietary diversity for women, household production diversity, farm income, women's empowerment and irrigation for the public irrigation scheme arrangement

Variables	MDD-W	Production diversity	Log of farm income (USD)	Women's empowerment	irrigation
Production diversity	-0.152*				
	(0.088)				
Log of farm income (USD)	0.012				
	(0.048)				
Women's empowerment	0.987*				
	(0.569)				
Household size	0.038		0.268***	0.001	-0.005
	(0.037)		(0.096)	(0.019)	(0.014)
Employed	-0.139				
	(0.139)				
Age of the household head (years)	-0.013*	0.012	-0.002	-0.003	0.002
	(0.007)	(0.011)	(0.019)	(0.004)	(0.003)
Age of the primary female decision maker (years)	0.012	-0.016	0.010	0.005	-0.004
	(0.007)	(0.011)	(0.020)	(0.004)	(0.003)
Tropical livestock units	0.414***	0.818***	1.287**	-0.027	0.016
	(0.114)	(0.106)	(0.549)	(0.037)	(0.027)
Education level of the household head (years)	0.003	0.011	0.173***	0.013	-0.013*
	(0.019)	(0.027)	(0.055)	(0.012)	(0.007)
Education level of the primary female decision maker (years)	0.031	0.004	-0.144**	-0.022*	0.021***
	(0.021)	(0.030)	(0.072)	(0.014)	(0.007)
Distance to the market (Kilometers)	0.032		0.049	0.016	-0.007
	(0.020)		(0.056)	(0.011)	(0.007)
Public irrigation scheme arrangement		-1.460***	6.494***	1.102**	
		(0.245)	(1.163)	(0.454)	
Assets (USD)		0.000			0.000
		(0.000)			(0.000)
Single adult household type		0.439**			
		(0.198)			
Primary female decision maker production decision		0.071	0.698	0.245***	-0.070
		(0.056)	(0.520)	(0.066)	(0.046)
Land owned (acres)		0.101**	0.439***	0.010	-0.010
		(0.044)	(0.115)	(0.015)	(0.011)
Household group membership		0.399**			0.136***
		(0.174)			(0.034)
Production diversity			-1.105		
			(0.734)		
Access to hybrid seed			-0.868	-0.102*	0.115***
			(0.609)	(0.059)	(0.039)
Access to fertilizer			1.412**	-0.077	0.076
			(0.712)	(0.127)	(0.073)
Land rental price (per acre)			-0.010***	-0.002**	0.002***
			(0.003)	(0.001)	(0.000)
Access to extra land				0.030	
				(0.123)	
Knowledge of pumping technology					0.065
					(0.04)
Single adult household type					0.069*
					(0.037)
Gender of the household head (Female)					-0.019
					(0.032)
Constant	3.689***	2.705***	4.226*	0.533***	-0.126
	(0.495)	(0.551)	(2.382)	(0.200)	(0.148)
Parameters	11	11	14	14	17
Equation root mean squared error	0.925	1.317	3.095	0.395	0.328
Equation R-squared	-0.043	0.276	-0.620	-4.197	0.498
Chi-square	36.480	144.810	122.420	137.680	307.500
Chi-square p-value	0.000	0.000	0.000	0.000	0.000
Number of observations	287	287	287	287	287

Note: Standard errors are listed below the coefficients in parentheses. † shows dummy variables. The notations and the meanings are as follows: *** p<.01, ** p<.05, and * p<.1

Source: Authors based on survey data.

6. Conclusion

The regression results clearly show that different irrigation arrangements achieve nutritional outcomes through different pathways and the factors that affects them are different. While in the aggregated results it shows that the three pathways of production diversity, farm income and women's empowerment were affected by irrigation, the disaggregated analysis shows that the pathways differ.

In the farmer-led irrigation arrangement analysis, production diversity neither influenced by this irrigation arrangement nor influence dietary diversity. In this irrigation arrangement, only farm income and women's diversity are plausible pathways for the households to higher dietary diversity.

While increase in income only translated to better nutritional outcomes for the households under farmer-led irrigation arrangement, it should not downplay also the significance of each of these irrigation arrangements increasing farm income. In an agro-based economy like Kenya, this plays a crucial role in improving the rural poverty. About 29% of the sampled households are under the rural poverty line as calculated by the country's official statistics. In addition, the average total annual income for the sampled households being at USD 1,912.35 and a mean sample household size of 4 persons, this indicates that most of the households are within the band of extreme poverty of spending less USD 2.15 per person per day at 2017 purchasing power parity. Therefore, investments in technologies that would improve the incomes of this population such as irrigation is needful. This finding that irrigation does lead to increased income is also congruent with similar finding in Nigeria (Burney & Naylor, 2012), Malawi (Mangisoni, 2008), Ethiopia (Passarelli et al., 2018), Ghana (Balana et al., 2020; Okyere & Usman, 2021) and in sub-Saharan Africa in general (Xie et al., 2014; You et al., 2011).

In addition, in the farmer-led irrigation arrangement, it is evident that such increase in incomes of such households is also spent on food which is supported by other evidences in research such as Banerjee & Duflo2007 and Zezza et al., (2009). This particular finding is of great importance to sub-Saharan Africa that is experiencing a policy intensity towards irrigation due to climate related challenges under a backdrop of dismal performance of large-scale water infrastructure such as large publicly funded irrigation schemes (Higginbottom et al., 2021). This has renewed an interest in farmer-led irrigation (de Bont et al., 2019; Woodhouse et al., 2017). This research provides evidence on the limitedly researched farmer-led irrigation arrangement especially as concerns the impact of incomes on nutrition. It is thus concluded that increased farm incomes from engagement in the farmer-led irrigation arrangement does translate to better household nutrition as measured through dietary diversity.

As argued in this research, the improvement of nutritional outcomes through irrigation depends on the irrigation arrangement and the design of the intervention. Similarly, the finding that irrigation leads to better nutritional outcome through increased income has been evidenced in Benin where the increase in income was spent on food, healthcare and education (Alaofè et al., 2016) and in India especially when supplemented by better health and education (Bhagowalia et al., 2012). In Ghana, irrigation was also associated with better nutrition outcomes for children (Okyere & Usman, 2021) and in Ethiopia where irrigation increased the diversity of households' diets through increased incomes (Passarelli et al., 2018).

The feasibility of the women's empowerment in both irrigation arrangements shows the importance of this pathway in relation to household nutrition. The finding concurs with previous research done that associates aspects of women's empowerment to improved diets (Anderson et al., 2021; Baye et al., 2021; Connors et al., 2023; Kassie et al., 2020; Komakech et al., 2022; Pandey et al., 2016; Sinharoy et al., 2018; Sraboni & Quisumbing, 2018; Vermes, 2021). There are particular reasons that could point as to why women's empowerment seems to transverse through all the irrigation arrangements as a means to achieve higher household nutritional outcomes. Women are the key caregivers and meal preparers in Kenya (Bukachi et al., 2022; Fingleton-Smith, 2018; Kassie et al., 2020; Okelo et al., 2022; Reiheld, 2014) . Therefore, given the power, their decisions will tend to influence the household nutrition. Secondly, when in control of income and decisions on resource use, research has shown that women tend to spend a considerable amount of these resources on household welfare including food and healthcare in a manner that does not compromise on the households nutritional needs (Bukachi et al., 2022).

Lastly, women's empowerment also enhances the welfare of the women themselves in an ability to make sure that their wellbeing is taken care of, In this way, the household's benefits directly and indirectly in relation to her resource use, care, time load and availability (Lépine & Strobl, 2013).

7. References

Agathokleous, E., Frei, M., Knopf, O. M., Muller, O., Xu, Y., Nguyen, T. H., Gaiser, T., Liu, X., Liu, B., & Saitanis, C. J. (2023). Adapting crop production to climate change and air pollution at different scales. *Nature Food*, 1–12.

Alaofè, H., Burney, J., Naylor, R., & Taren, D. (2016). Solar-Powered Drip Irrigation Impacts on Crops Production Diversity and Dietary Diversity in Northern Benin. *Food and Nutrition Bulletin*, *37*(2), 164–175. https://doi.org/10.1177/0379572116639710

Alkire, S., Meinzen-Dick, R., Peterman, A., Quisumbing, A., Seymour, G., & Vaz, A. (2013). The women's empowerment in agriculture index. *World Development*, *52*, 71–91.

Altchenko, Y., & Villholth, K. G. (2015). Mapping irrigation potential from renewable groundwater in Africa – a quantitative hydrological approach. *Hydrology and Earth System Sciences*, *19*(2), 1055–1067. https://doi.org/10.5194/hess-19-1055-2015

Anderson, C. L., Reynolds, T. W., Biscaye, P., Patwardhan, V., & Schmidt, C. (2021). Economic benefits of empowering women in agriculture: Assumptions and evidence. *The Journal of Development Studies*, *57*(2), 193–208.

Balana, B. B., Bizimana, J.-C., Richardson, J. W., Lefore, N., Adimassu, Z., & Herbst, B. K. (2020). Economic and food security effects of small-scale irrigation technologies in northern Ghana. *Water Resources and Economics*, *29*, 100141.

Banerjee, A. V., & Duflo, E. (2007). The economic lives of the poor. *Journal of Economic Perspectives*, *21*(1), 141–167.

Basmann, R. L. (1960). On finite sample distributions of generalized classical linear identifiability test statistics. *Journal of the American Statistical Association*, *55*(292), 650–659.

Baye, K., Laillou, A., & Chitekwe, S. (2021). Empowering women can improve child dietary diversity in Ethiopia. *Maternal & Child Nutrition*, e13285.

BenYishay, A., Goodman, S., Sayers, R., Singh, K., Walker, M., Rauschenbach, M., & Noltze, M. (2023). Does Irrigation Strengthen Climate Resilience? A Geospatial Impact Evaluation of Interventions in Mali, DEval Discussion Paper 1/2023, German Institute for Development Evaluation (DEval), Bonn. *German Institute for Development Evaluation (DEval), May 2023*.

Berti, P. R. (2015). Relationship between production diversity and dietary diversity depends on how number of foods is counted. *Proceedings of the National Academy of Sciences*, *112*(42), E5656–E5656.

Bhagowalia, P., Kadiyala, S., & Headey, D. (2012). *Agriculture, income and nutrition linkages in India: Insights from a nationally representative survey.*

Bhattarai, M., Sakthivadivel, R., & Hussain, I. (2001). *Irrigation impacts on income inequality and poverty alleviation: Policy issues and options for improved management of irrigation systems* (Vol. 39). IWMI.

Bjorneberg, D. L., & Sojka, R. E. (2005). IRRIGATION | Methods. In D. Hillel (Ed.), *Encyclopedia of Soils in the Environment* (pp. 273–280). Elsevier. https://doi.org/10.1016/B0-12-348530-4/00276-9

Brown, E., Mwangi-Powell, F., Jerotich, M., & le May, V. (2016). Female Genital Mutilation in Kenya: Are young men allies in social change programmes? *Reproductive Health Matters*, *24*(47), 118–125.

Bukachi, S. A., Ngutu, M., Muthiru, A. W., Lépine, A., Kadiyala, S., & Domínguez-Salas, P. (2022). Gender and sociocultural factors in animal source foods (ASFs) access and consumption in lower-income households in urban informal settings of Nairobi, Kenya. *Journal of Health, Population and Nutrition*, *41*(1), 1–9.

Burney, J. A., & Naylor, R. L. (2012). Smallholder irrigation as a poverty alleviation tool in sub-Saharan Africa. *World Development*, *40*(1), 110–123.

Chokkakula, S., & Giordano, M. (2013). Do policy and institutional factors explain the low levels of smallholder groundwater use in Sub-Saharan Africa? *Water International*, *38*(6), 790–808.

Closas, A., & Rap, E. (2017). Solar-based groundwater pumping for irrigation: Sustainability, policies, and limitations. *Energy Policy*, *104*, 33–37.

Cochran, W. G. (1963). *Sampling techniques* (2nd Edition). John Wiley and Sons Inc., New York.

Connors, K., Jaacks, L. M., Awasthi, A., Becker, K., Kerr, R. B., Fivian, E., Gelli, A., Harris-Fry, H., Heckert, J., & Kadiyala, S. (2023). Women's empowerment, production choices, and crop diversity in Burkina Faso, India, Malawi, and Tanzania: A secondary analysis of cross-sectional data. *The Lancet Planetary Health*, *7*(7), e558–e569.

de Bont, C., Komakech, H. C., & Veldwisch, G. J. (2019). Neither modern nor traditional: Farmer-led irrigation development in Kilimanjaro Region, Tanzania. *World Development*, *116*, 15–27.

De Wrachien, D., Schultz, B., & Goli, M. B. (2021). Impacts of population growth and climate change on food production and irrigation and drainage needs: A world-wide view. *Irrigation and Drainage*, *70*(5), 981–995.

Deaton, A. (2019). *The analysis of household surveys (reissue edition with a new preface): A microeconometric approach to development policy*. World Bank Publications.

Devi, S. (2023). Kenya introduces huge school meals programme. *The Lancet*, *402*(10397), 173.

Domènech, L. (2015). Improving irrigation access to combat food insecurity and undernutrition: A review. *Global Food Security*, *6*, 24–33. https://doi.org/10.1016/j.gfs.2015.09.001

Domenèch, L., & Ringler, C. (2013). *The impact of irrigation on nutrition, health, and gender: A review paper with insights for Africa south of the Sahara*.

Durga, N., Schmitter, P., Ringler, C., Mishra, S., Magombeyi, M. S., Ofosu, A., Pavelic, P., Hagos, F., Melaku, D., & Verma, S. (2024). Barriers to the uptake of solar-powered irrigation by smallholder farmers in sub-saharan Africa: A review. *Energy Strategy Reviews*, *51*, 101294.

Fan, S., & Pandya-Lorch, R. (2012). *Reshaping agriculture for nutrition and health*. Intl Food Policy Res Inst.

FAO. (2021). *Minimum dietary diversity for women.* Rome: FAO. https://doi.org/10.4060/cb3434en

FAO. (2023). *Food and Agricultural Organization of the United Nations (FAO) FAOSTAT Statistical Database*. https://www.fao.org/faostat/en/

FAO, & FHI 360. (2016). *Minimum Dietary Diversity for Women: A Guide for Measurement.* Rome: FAO. https://www.fao.org/3/i5486e/i5486e.pdf

FAO, IFAD, UNICEF, WFP, WHO. (2023). *The State of Food Security and Nutrition in the World 2023*. FAO; IFAD; UNICEF; WFP; WHO; https://doi.org/10.4060/cc3017en

Fingleton-Smith, E. (2018). The lights are on but no (men) are home. The effect of traditional gender roles on perceptions of energy in Kenya. *Energy Research & Social Science*, *40*, 211–219.

Flax, V. L., Ouma, E. A., Baltenweck, I., Omosa, E., Girard, A. W., Jensen, N., & Dominguez-Salas, P. (2023). Pathways from livestock to improved human nutrition: Lessons learned in East Africa. *Food Security*, *15*(5), 1293–1312.

Friedman, S. P. (2023). Irrigation methods. In M. J. Goss & M. Oliver (Eds.), *Encyclopedia of Soils in the Environment (Second Edition)* (pp. 608–623). Academic Press. https://doi.org/10.1016/B978-0-12-822974-3.00138-5

Gebre, G. G., Amekawa, Y., & Fikadu, A. A. (2023). Farmers' use of climate change adaptation strategies and their impacts on food security in Kenya. *Climate Risk Management*, *40*, 100495.

Gillespie, S., & van den Bold, M. (2017). Agriculture, food systems, and nutrition: Meeting the challenge. *Global Challenges*, *1*(3), 1600002.

Hanjra, M. A., & Williams, T. O. (2020). Global change and investments in smallholder irrigation for food and nutrition security in Sub-Saharan Africa. *The Role of Smallholder Farms in Food and Nutrition Security*, 99–131.

Hansen, L. P. (1982). Large sample properties of generalized method of moments estimators. *Econometrica: Journal of the Econometric Society*, 1029–1054.

Hatch, N. R., Daniel, D., & Pande, S. (2022). Behavioral and socio-economic factors controlling irrigation adoption in Maharashtra, India. *Hydrological Sciences Journal*, *67*(6), 847–857.

Hawkes, C., & Ruel, M. T. (2012). Value chains for nutrition. *Reshaping Agriculture for Nutrition and Health*, 73–82.

Herforth, A., & Harris, J. (2014). *Understanding and applying primary pathways and principles. Brief# 1. Improving nutrition through agriculture technical brief series*. Arlington, VA: USAID/Strengthening Partnerships, Results, and Innovations in Nutrition Globally (SPRING) Project.

Higginbottom, T. P., Adhikari, R., Dimova, R., Redicker, S., & Foster, T. (2021). Performance of large-scale irrigation projects in sub-Saharan Africa. *Nature Sustainability*, *4*(6), 501–508.

Hjalmarsdottir, E. H. (2012). Solar powered pumping technologies in rural water supply: Case study from Kunene region, Namibia. *Waterlines*, 197–214.

Hornum, S. T., & Bolwig, S. (2020). *The Growth of Small-Scale Irrigation in Kenya: The Role of Private Firms in Technology Diffusion*.

Hussain, I., & Wijerathna, D. (2004). *Irrigation and Income-Poverty Alleviation: A Comparative Analysis of Irrigation Systems in Developing Asia*. 42.

IPCC. (2023). *IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland.* (First). Intergovernmental Panel on Climate Change (IPCC). https://doi.org/10.59327/IPCC/AR6-9789291691647

Israel, G. D. (1992). *Sampling the evidence of extension program impact*. Citeseer.

Jaenicke, H., & Virchow, D. (2013). Entry points into a nutrition-sensitive agriculture. *Food Security*, *5*, 679–692.

Jodlowski, M., Winter-Nelson, A., Baylis, K., & Goldsmith, P. D. (2016). Milk in the data: Food security impacts from a livestock field experiment in Zambia. *World Development*, *77*, 99–114.

Kafle, K., Omotilewa, O., & Leh, M. (2020). Who benefits from farmer-led irrigation expansion in Ethiopia? *African Development Bank Working Paper*.

Kamwamba-Mtethiwa, J., Weatherhead, K., & Knox, J. (2016). Assessing performance of small-scale pumped irrigation systems in sub-Saharan Africa: Evidence from a systematic review. *Irrigation and Drainage*, *65*(3), 308–318.

Kassie, M., Fisher, M., Muricho, G., & Diiro, G. (2020). Women's empowerment boosts the gains in dietary diversity from agricultural technology adoption in rural Kenya. *Food Policy*, *95*, 101957.

Kennedy, G., & Ballard, T. (2011). *Kennedy, G., Ballard, T., & Dop, M. C. (2011). Guidelines for measuring household and individual dietary diversity. Food and Agriculture Organization of the United Nations.* https://www.fao.org/3/i1983e/i1983e00.pdf

Kloezen, W., & Mollinga, P. P. (1992). Opening closed gates: Recognizing the social nature of irrigation artefacts. In *Irrigators and engineers* (pp. 53–64). Thesis Publ.

Kloezen, W., & Van Bentum, M. (1993). The labour aspect in the choice of irrigation technology in Torre Pacheco, south-east Spain. *International Journal of Water Resources Development*, *9*(1), 27–37.

Komakech, J. J., Walters, C. N., Rakotomanana, H., Hildebrand, D. A., & Stoecker, B. J. (2022). The associations between women's empowerment measures, child growth and dietary diversity: Findings from an analysis of demographic and health surveys of seven countries in Eastern Africa. *Maternal & Child Nutrition*, *18*(4), e13421. https://doi.org/10.1111/mcn.13421

Kornher, L., & von Braun, J. (2023). *The Global Food Crisis Will Not Be Over When International Prices Are Back to Normal* (SSRN Scholarly Paper 4337413). https://doi.org/10.2139/ssrn.4337413

LaFevor, M. C., & Pitts, A. K. (2022). Irrigation Increases Crop Species Diversity in Low-Diversity Farm Regions of Mexico. *Agriculture*, *12*(7), Article 7. https://doi.org/10.3390/agriculture12070911

Lankford, B. (2009). Viewpoint—The right irrigation? Policy directions for agricultural water management in sub-Saharan Africa. *Water Alternatives*, *2*(3), 476–480.

Leal Filho, W., Ayal, D. Y., Chamma, D. D., Kovaleva, M., Alverio, G. N., Nzengya, D. M., Mucova, S. A. R., Kalungu, J. W., & Nagy, G. J. (2023). Assessing causes and implications of climate-induced migration in Kenya and Ethiopia. *Environmental Science & Policy*, *150*, 103577.

Lépine, A., & Strobl, E. (2013). The effect of women's bargaining power on child nutrition in rural Senegal. *World Development*, *45*, 17–30.

Li, J., Ma, W., Renwick, A., & Zheng, H. (2020). The impact of access to irrigation on rural incomes and diversification: Evidence from China. *China Agricultural Economic Review*, *12*(4), 705–725. https://doi.org/10.1108/CAER-09-2019-0172

Lin, F., Li, X., Jia, N., Feng, F., Huang, H., Huang, J., Fan, S., Ciais, P., & Song, X.-P. (2023). The impact of Russia-Ukraine conflict on global food security. *Global Food Security*, *36*, 100661. https://doi.org/10.1016/j.gfs.2022.100661

Liu, W., Zhou, J., Ma, Y., Chen, S., & Luo, Y. (2023). *Climate warming creates an unequal burden on global cattle meat yields*.

Malapit, H. J., Pinkstaff, C., Sproule, K., Kovarik, C., Quisumbing, A. R., & Meinzen-Dick, R. S. (2017). *The abbreviated women's empowerment in agriculture index (A-WEAI)*.

Malapit, H., Kovarik, C., Sproule, K., Meinzen-Dick, R., & Quisumbing, A. (2015). Instructional guide on the abbreviated women's empowerment in agriculture index (A-WEAI). *Washington, DC: International Food Policy Research Institute*.

Mangisoni, J. H. (2008). Impact of treadle pump irrigation technology on smallholder poverty and food security in Malawi: A case study of Blantyre and Mchinji districts. *International Journal of Agricultural Sustainability*, *6*(4), 248–266.

Marigi, S. N. (2017). Climate change vulnerability and impacts analysis in Kenya. *American Journal of Climate Change*, *6*(01), 52.

Mati, B. M. (2008). Capacity development for smallholder irrigation in Kenya. *Irrigation and Drainage: The Journal of the International Commission on Irrigation and Drainage*, *57*(3), 332–340.

Mollinga, P. P. (1998). *On the waterfront: Water distribution, technology and agrarian change in a South Indian canal irrigation system*. Wageningen University and Research.

Mollinga, P. P. (2003). *On the Waterfront. Water Distribution, Technology and Agrarian Change in a South Indian Canal Irrigation System*.

Momanyi, V. N., N. Keraka, M., A. Abong'o, D., & N. Warutere, P. (2019). Types and Classification of Pesticides Used on Tomatoes Grown in Mwea Irrigation Scheme, Kirinyaga County, Kenya. *European Journal of Nutrition & Food Safety*, 83–97. https://doi.org/10.9734/ejnfs/2019/v11i230145

Mueller, N. D., Gerber, J. S., Johnston, M., Ray, D. K., Ramankutty, N., & Foley, J. A. (2012). Closing yield gaps through nutrient and water management. *Nature*, *490*(7419), Article 7419. https://doi.org/10.1038/nature11420

Muthayya, S., Rah, J. H., Sugimoto, J. D., Roos, F. F., Kraemer, K., & Black, R. E. (2013). The global hidden hunger indices and maps: An advocacy tool for action. *PloS One*, *8*(6), e67860.

Narain, V., & Singh, A. K. (2017). Flowing against the current: The socio-technical mediation of water (in) security in periurban Gurgaon, India. *Geoforum*, *81*, 66–75.

National Irrigation Authority. (2019). *National Irrigation Authority Strategic Plan (2019–2023)*. https://www.irrigation.go.ke/strategic-plan/

National Police Service. (2017). *Community Policing Information Booklet*. National Police Service. Government of Kenya. https://www.nationalpolice.go.ke/downloads/category/20-nps-community-policing-information-booklet.html

Ndono, P. W., Muthama, N. J., & Muigua, K. (2019). Effectiveness of the Nyumba Kumi community policing initiative in Kenya. *Journal of Sustainability, Environment and Peace*, *1*(2), 63–67.

Njoka, J. T., Yanda, P., Maganga, F., Liwenga, E., Kateka, A., Henku, A., Mabhuye, E., Malik, N., & Bavo, C. (2016). Kenya: Country situation assessment. *Pathways to Resilience in Semi-Arid Economies (PRISE)*.

Okelo, K., Onyango, S., Murdock, D., Cordingley, K., Munsongo, K., Nyamor, G., & Kitsao-Wekulo, P. (2022). Parent and implementer attitudes on gender-equal caregiving in theory and practice: Perspectives on the impact of a community-led parenting empowerment program in rural Kenya and Zambia. *Bmc Psychology*, *10*(1), 1–11.

Okyere, C. Y., & Usman, M. A. (2021). The impact of irrigated agriculture on child nutrition outcomes in southern Ghana. *Water Resources and Economics*, *33*, 100174.

Otte, J., Costales, A., Dijkman, J., Pica-Ciamarra, U., Robinson, T., Ahuja, V., Ly, C., & Roland-Holst, D. (2012). *Livestock Sector Development for Poverty Reduction: An Economic and Policy Perspective Livestock Many Virtues*. Food and Agriculture Organization of the United Nations Rome.

Pandey, V. L., Dev, S. M., & Jayachandran, U. (2016). Impact of agricultural interventions on the nutritional status in South Asia: A review. *Food Policy*, *62*, 28–40.

Passarelli, S., Mekonnen, D., Bryan, E., & Ringler, C. (2018). Evaluating the pathways from small-scale irrigation to dietary diversity: Evidence from Ethiopia and Tanzania. *Food Security*, *10*(4), 981–997. https://doi.org/10.1007/s12571-018-0812-5

Rahut, D. B., Aryal, J. P., Manchanda, N., & Sonobe, T. (2022). Chapter 6 - Expectations for household food security in the coming decades: A global scenario. In R. Bhat (Ed.), *Future Foods* (pp. 107–131). Academic Press. https://doi.org/10.1016/B978-0-323-91001-9.00002-5

Rao, T., & Pingali, P. (2018). The role of agriculture in women’s nutrition: Empirical evidence from India. *PLoS ONE*, *13*(8), e0201115. https://doi.org/10.1371/journal.pone.0201115

Reiheld, A. (2014). *Gender norms and food behaviors*.

Rosa, L., Chiarelli, D. D., Sangiorgio, M., Beltran-Peña, A. A., Rulli, M. C., D’Odorico, P., & Fung, I. (2020a). Potential for sustainable irrigation expansion in a 3 C warmer climate. *Proceedings of the National Academy of Sciences*, *117*(47), 29526–29534.

Rosa, L., Chiarelli, D. D., Sangiorgio, M., Beltran-Peña, A. A., Rulli, M. C., D’Odorico, P., & Fung, I. (2020b). Potential for sustainable irrigation expansion in a 3 C warmer climate.

Proceedings of the National Academy of Sciences, *117*(47), 29526–29534.

Ruel, M. T., Quisumbing, A. R., & Balagamwala, M. (2018). Nutrition-sensitive agriculture: What have we learned so far? *Global Food Security*, *17*, 128–153.

Salm-Reifferscheidt, L. (2023). One Health in Kenya. *The Lancet*, *401*(10372), 182–183.

Sargan, J. D. (1958). The estimation of economic relationships using instrumental variables. *Econometrica: Journal of the Econometric Society*, 393–415.

Sauer, T., Havlík, P., Schneider, U. A., Schmid, E., Kindermann, G., & Obersteiner, M. (2010). Agriculture and resource availability in a changing world: The role of irrigation. *Water Resources Research*, *46*(6).

Shahid, S. A., & Al-Shankiti, A. (2013). Sustainable food production in marginal lands—Case of GDLA member countries. *International Soil and Water Conservation Research*, *1*(1), 24–38.

Sibhatu, K. T., Krishna, V. V., & Qaim, M. (2015a). Production diversity and dietary diversity in smallholder farm households. *Proceedings of the National Academy of Sciences*, *112*(34), 10657–10662.

Sibhatu, K. T., Krishna, V. V., & Qaim, M. (2015b). Reply to Berti: Relationship between production and consumption diversity remains small also with modified diversity measures. *Proceedings of the National Academy of Sciences*, *112*(42), E5657–E5657.

Sinharoy, S. S., Waid, J. L., Haardörfer, R., Wendt, A., Gabrysch, S., & Yount, K. M. (2018). Women's dietary diversity in rural Bangladesh: Pathways through women's empowerment. *Maternal & Child Nutrition*, *14*(1), e12489.

Sraboni, E., & Quisumbing, A. (2018). Women's empowerment in agriculture and dietary quality across the life course: Evidence from Bangladesh. *Food Policy*, *81*, 21–36.

SPRING. 2014. Understanding the Agricultural Income Pathway. Brief 3. Improving Nutrition through Agriculture Technical Brief Series. Arlington, VA: USAID/Strengthening Partnerships, Results, and Innovations in Nutrition Globally (SPRING) Project

Tomizuka, T., Mwithia, D., & Koskei, V. (2019). Secondary horticultural cropping in a paddy field in the Mwea irrigation scheme, Kenya: Different drainage techniques and effect on selected crop yields. *Tropical Agriculture and Development*, *63*(2), 61–68.

United Nations. (2015). *The Millennium Development Goals Report 2015*. https://www.un.org/millenniumgoals/2015_MDG_Report/pdf/MDG%202015%20rev%20(July%201).pdf

Uphoff, N. T. (1986). *Getting the process right: Improving irrigation water management with farmer organization and participation*. Cornell University Ithaca, NY, USA.

Van der Kooij, S., Zwarteveen, M., & Kuper, M. (2015). The material of the social: The mutual shaping of institutions by irrigation technology and society in Seguia Khrichfa, Morocco. *International Journal of the Commons*, *9*(1).

van Maanen, N., Andrijevic, M., Lejeune, Q., Rosa, L., Lissner, T., & Schleussner, C.-F. (2022). Accounting for socioeconomic constraints in sustainable irrigation expansion assessments. *Environmental Research Letters*, *17*(7), 075004.

Vermes, E. (2021). *Women's Empowerment and Dietary Diversity: Differential Impacts of Agency*.

Wang, D., Liang, Y., Liu, L., Huang, J., & Yin, Z. (2023). Crop production on the Chinese Loess Plateau under 1.5 and 2.0° C global warming scenarios. *Science of The Total Environment*, *903*, 166158.

Wang, L., Jiao, W., MacBean, N., Rulli, M. C., Manzoni, S., Vico, G., & D'Odorico, P. (2022). Dryland productivity under a changing climate. *Nature Climate Change*, *12*(11), 981–994.

Wang, X., Müller, C., Elliot, J., Mueller, N. D., Ciais, P., Jägermeyr, J., Gerber, J., Dumas, P., Wang, C., Yang, H., Li, L., Deryng, D., Folberth, C., Liu, W., Makowski, D., Olin, S., Pugh, T. A. M., Reddy, A., Schmid, E., … Piao, S. (2021). Global irrigation contribution to wheat and maize yield. *Nature Communications*, *12*(1), Article 1. https://doi.org/10.1038/s41467-021-21498-5

Wazed, S. M., Hughes, B. R., O'Connor, D., & Calautit, J. K. (2018). A review of sustainable solar irrigation systems for Sub-Saharan Africa. *Renewable and Sustainable Energy Reviews*, *81*, 1206–1225.

Webb, P., & Kennedy, E. (2014). Impacts of agriculture on nutrition: Nature of the evidence and research gaps. *Food and Nutrition Bulletin*, *35*(1), 126–132.

Wichelns, D., & Oster, J. D. (2006). Sustainable irrigation is necessary and achievable, but direct costs and environmental impacts can be substantial. *Agricultural Water Management*, *86*(1–2), 114–127.

Woodhouse, P., Veldwisch, G. J., Venot, J.-P., Brockington, D., Komakech, H., & Manjichi, Â. (2017). African farmer-led irrigation development: Re-framing agricultural policy and investment? *The Journal of Peasant Studies*, *44*(1), 213–233.

World Bank. (2021). *Farmer-led Irrigation Development (FLID)* [Text/HTML]. World Bank. https://www.worldbank.org/en/topic/water/brief/farmer-led-irrigation-development-flid

World Bank. (2023). *The World Bank Databank.* http://databank.worldbank.org/data/

Xie, H., Ringler, C., & Mondal, M. A. H. (2021). Solar or diesel: A comparison of costs for groundwater-fed irrigation in sub-Saharan Africa under two energy solutions. *Earth's Future*, *9*(4), e2020EF001611.

Xie, H., You, L., Wielgosz, B., & Ringler, C. (2014). Estimating the potential for expanding smallholder irrigation in Sub-Saharan Africa. *Agricultural Water Management*, *131*, 183–

193.

You, L., Ringler, C., Wood-Sichra, U., Robertson, R., Wood, S., Zhu, T., Nelson, G., Guo, Z., & Sun, Y. (2011). What is the irrigation potential for Africa? A combined biophysical and socioeconomic approach. *Food Policy*, *36*(6), 770–782. https://doi.org/10.1016/j.foodpol.2011.09.001

Zellner, A., & Theil, H. (1962). Three-Stage Least Squares: Simultaneous Estimation of Simultaneous Equations. *Econometrica*, *30*(1), 54–78. https://doi.org/10.2307/1911287

Zezza, A., Davis, B., Azzarri, C., Covarrubias, K., Tasciotti, L., & Anriquez, G. (2009). *The impact of rising food prices on the poor*.

Zhu, P., Burney, J., Chang, J., Jin, Z., Mueller, N. D., Xin, Q., Xu, J., Yu, L., Makowski, D., & Ciais, P. (2022). Warming reduces global agricultural production by decreasing cropping frequency and yields. *Nature Climate Change*, *12*(11), 1016–1023.