

Research Article

Evaluating the Rice Crop Water Productivity of Irrigation Schemes Practicing Continuous Flooding Irrigation Regime: A Case Study of Ahero Irrigation Scheme in Kenya

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Abstract

The growing scarcity of freshwater resources presents a major challenge to rice production particularly in irrigation systems that rely on limited freshwater supplies. Enhancing the water use efficiency has therefore become essential for sustainable rice cultivation. This study evaluated the rice crop water productivity under continuous flooding irrigation regime using the Ahero Irrigation Scheme in Kenya as a case study. The rice crop water productivity was determined as the ratio of the total mass of rice production to the total volume of water supplied for irrigation. The rice crop water productivity for the scheme was measured and found to be 0.3406 kgm^{-3} . The measured value was lower than what is commonly achieved under improved irrigation regimes such as intermittent irrigation. The low water productivity was mainly attributed to conveyance losses along the earthen canals and application losses due to inefficient irrigation practices. Improving the water productivity requires several interventions; lining and maintenances of canals to reduce conveyance losses, adopting intermittent irrigation to use less irrigation water resource, training farmers on proper land preparation techniques to enhance leveling in the irrigation basins thereby reducing excessive irrigation water application in unlevelled basins, and strengthening the capacity of Irrigation Water Users Associations to monitor and enforce proper irrigation water usage.

Keywords

Rice Crop Water Productivity, Crop Water Productivity, Water Productivity, Water Use Efficiency, Continuous Flooding Irrigation, Application Losses, Conveyance Losses

1. Introduction

The global demand for food continues to rise rapidly due to the exponential growth of the human population. The world's population surpassed 8 billion in the year 2022 [1]. This increase places significant pressure on agricultural systems to produce sufficient food for human consumption. There is need to enhance food production to ensure zero hunger, achieve food security, and improve nutrition [2]. The global

population relies heavily on rice as a primary staple food [3]. Rice serves as an essential dietary component for many people particularly across Asia and Africa [4]. Rice is one of the most water-demanding crop despite being an essential food crop. The irrigation water used in rice production accounts for about 30-40% of the world's freshwater abstracted for agriculture [5, 6]. The growing scarcity of freshwater resources

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presents a major challenge to rice production especially in irrigation systems that depend on limited freshwater supplies for rice crop cultivation [7].

The efficient use of available fresh water resources has therefore become crucial in sustaining rice production. The crop water productivity is an important measure of sustainability describing how efficiently irrigation water is utilized in crop production in irrigation systems [8]. Improving the crop water productivity in irrigation systems helps conserve irrigation water, lower production costs, and increase the income received by farmers [9].

The crop water productivity indicator represents the ratio of the mass of crop production obtained to the total volume of irrigation water supplied to the crop used in the production process [10]. The total volume of irrigation water supplied to a crop is quantified by summing the volume of irrigation water abstracted from various sources together with the volume of water received by the crop as effective rainfall [11]. Effective rainfall refers to the portion of the total rainfall that contributes to meeting the crop water needs after accounting for losses such as deep percolation and runoff [12]. The total volume of water received as effective rainfall is commonly calculated by multiplying the depth of effective rainfall by the total cropped area [12]. There are several methods existing for estimating the amount of effective rainfall including the dependable rainfall method, empirical formula method, fixed percentage of rainfall method, and the USDA Soil Conservation Service (SCS) method [13].

There are several factors that affect the rice crop water productivity such as the soil characteristics, irrigation methods, water availability and management practices, crop variety, and the prevailing climatic conditions [14, 15]. Soils with high permeability leads to significant percolation losses thereby reducing water productivity [16]. Improved irrigation methods such as alternate wetting and drying (AWD) have shown to enhance water productivity by minimizing irrigation water losses [17]. The availability and management of irrigation water directly influence the water-use efficiency and the overall productivity in rice irrigation systems [18]. Drought-tolerant and early-maturing rice varieties tend to achieve higher yields under limited water conditions [19, 20]. Climatic conditions such as temperature, rainfall variability, relative humidity, and evapotranspiration rates greatly affect the rice crop water productivity [21].

The rice crop can be irrigated using different methods primarily through continuous flooding and intermittent irrigation [22, 23]. The continuous flooding is the most common and traditional method in which paddy irrigation basins remain continuously submerged under water maintaining fully saturated soil conditions throughout most of the crop growing season [24]. The rice crop water productivity under continuous flooding typically ranges between 0.2 and 0.4 kgm⁻³ [6]. The intermittent irrigation also known as alternate wetting and drying (AWD) is an improved method that involves periodically drying the field between irrigation allowing the rice crop

to grow under both saturated and unsaturated soil conditions [22, 23]. The rice crop water productivity under intermittent irrigation is substantially higher typically ranging from 0.6 to 1.5 kgm⁻³ [15].

Efficiency can be expressed as a ratio of output to input [25]. Conveyance efficiency is a ratio of the quantity of water delivered to the irrigated fields through various transport systems to the quantity of irrigation water abstraction from a source [26]. Application efficiency is a ratio of the irrigation water that is directly available to the crop at the root zone compared to the amount of irrigation water the irrigated field received from its inlet [27]. Irrigation efficiency is a product of conveyance and application efficiencies [25]. Distribution efficiency also known as Christiansen's uniformity coefficient measures the uniformity of irrigation water distribution in terms of depth over the field after irrigation [28, 29]. Enhancing these efficiencies minimizes irrigation water losses and increases the volume of irrigation water available for productive agricultural use.

The management of irrigation schemes and the Irrigation Water Users Associations (WUAs) play vital roles in promoting the sustainable utilization of irrigation water resources. The scheme's management are responsible for maintaining irrigation water conveyance infrastructure, regulating irrigation water distribution among users, and enforcing irrigation water allocation schedules [30, 31]. The WUAs are instrumental in fostering collective action among farmers, minimizing water-use conflicts among users, and ensuring equitable and efficient distribution of irrigation water within the system [32]. The effective governance of irrigation water resources along with the proper maintenance of irrigation and drainage infrastructure is therefore essential to achieving higher irrigation and water-use efficiencies.

The understanding of how irrigation regimes influence the rice crop water productivity is critical because it informs the schemes' managers on how to improve crop production with limited irrigation water resources. Therefore, this study aims to evaluate the rice crop water productivity under continuous flooding irrigation regime using the Ahero Irrigation Scheme in Kenya as a case study. The findings are expected to provide valuable insights to inform strategies for enhancing the rice crop water productivity using limited irrigation water resource for irrigation schemes facing similar challenges such as Ahero Irrigation Scheme in Kenya.

2. Research Methods

2.1. Study Area

The Ahero Irrigation Scheme is situated in the western part of Kenya within Kisumu County, see Figure 1. The scheme geographically lies within the tropical zone and can be located using GPS coordinates ranging between latitudes 0.125 °S and 0.175 °S, and longitudes 34.905 °E and 34.975 °E. The irrigation water used in the scheme is abstracted from River

Nyando. The irrigation water is diverted from River Nyando using four electrically driven pumps installed at the pumping station. The diverted irrigation water is then delivered into the earthen main canal for conveyance, see Figure 2. The irrigation water is then conveyed via gravity through a network of

canals starting from the earthen main canal to the secondary earthen canals and finally to the tertiary earthen canals. The continuous flooding irrigation method is used to apply water to the rice crop grown in the irrigation basins [33].

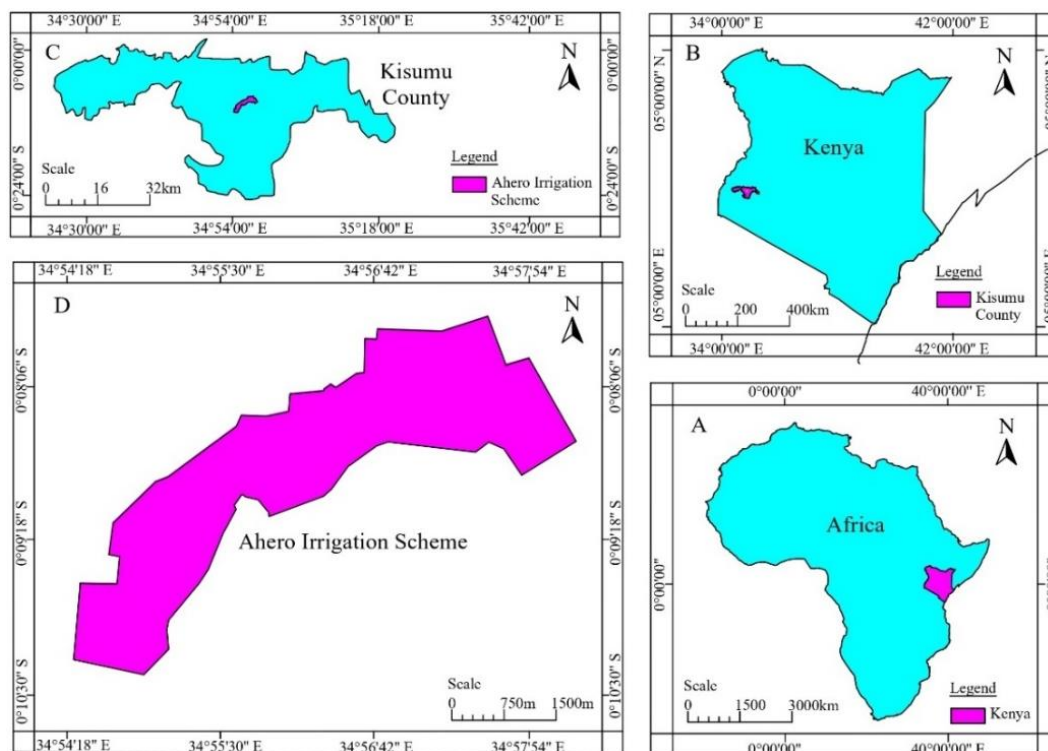


Figure 1. Geographical Location of Ahero Irrigation Scheme.

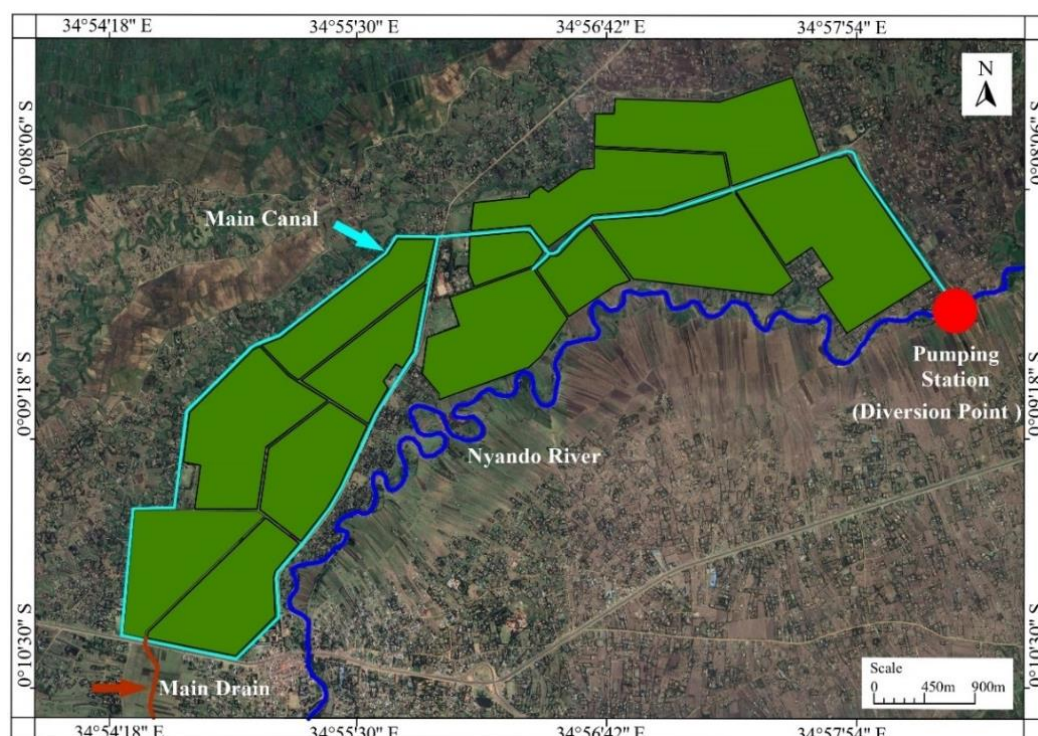


Figure 2. Aerial Satellite Imagery of Ahero Irrigation Scheme (Source; Google Earth, 2025).

2.2. Mass of Crop Production (Mc)

The value of the mass of crop production (Mc) was calculated by summing the monthly produce of the scheme for the entire cropping season which was a period of 12 months. The mass of the produce was measured in kilograms (Kgs).

2.3. Volume of Water Supplied (Vs)

The value of the volume of water supplied (Vs) for the entire cropping season was obtained by summing the annual volume of pumped irrigation water (Vp) at the pumping station and the annual volume of water received as effective rainfall (Vr) by the scheme [11]. The value of the volume of water supplied was calculated as indicated by Equation (1). The measured volume of water supplied was quantified in cubic meters.

$$V_s = V_p + V_r \quad (1)$$

2.3.1. Volume of Pumped Irrigation Water (Vp)

The value of the total annual volume of pumped irrigation water was determined at the pumping station which was the abstraction point as the quantity of water diverted from the source, River Nyando. This volume of water was quantified by calculating the product of the total pumping duration and the operating discharge rates of the pumps. The measured volume of pumped irrigation water was quantified in cubic meters.

2.3.2. Volume of Water as Effective Rainfall (Vr)

The value of the total annual volume of water received by the scheme as effective rainfall was obtained by multiplying the depth of effective rainfall by the total cropped area within the scheme. The depth of effective rainfall was calculated using the USDA-Soil Conservation Method in-built in CROPWAT 8 software [34]. The measured volume of water received as effective rainfall was quantified in cubic meters.

2.4. The Rice Crop Water Productivity (CWP)

The value of the rice crop water productivity was determined as the ratio of the mass of crop production (Mc) obtained by the scheme in the entire cropping season of one year to the total volume of water supplied (Vs) to the scheme during the same period [10]. The rice crop water productivity ratio was computed using Equation (2).

$$CWP = \frac{Mc}{V_s} \quad (2)$$

3. Results

3.1. Computation of the Mass of Crop Production (Mc)

The value of the mass of crop production in kilograms was obtained by adding the monthly yield recorded in the scheme in the entire cropping season a period of twelve months. The results of this computation are presented in Table 1.

Table 1. Mass of Crop Production (Mc).

Months	Production (Kg)
Apr 2022	1,167,878
May 2022	516,878
Jun 2022	0
Jul 2022	179,200
Aug 2022	328,200
Sep 2022	226,800
Oct 2022	1,397,600
Nov 2022	322,000
Dec 2022	0
Jan 2023	867,370
Feb 2023	561,730
Mar 2023	189,300
Total	5,756,956

3.2. Computation of the Volume of Water Supplied (Vs)

The computed value of the annual volume of water supplied in cubic meters was calculated by summing the total volume of pumped irrigation water in a year and the total volume of water received as effective rainfall by the scheme in a year as illustrated by Equation (3). The value of the total volume of pumped irrigation water in cubic meters was drawn from Table 2. The value of the total volume of water received as effective rainfall by the scheme in cubic meters was drawn from Table 3.

$$V_s = 13,908,174.84 + 2,994,177.10 = 16,902,351.94 \quad (3)$$

3.2.1. Volume of Pumped Irrigation Water (Vp)

The value of the volume of pumped irrigation water diverted into the scheme in the entire cropping season of one year in cubic meters was calculated by finding the product of the total pumping duration and the operating discharge rates of the pumps. The results of this computation are presented in

Table 2, [26].

Table 2. Volume of Pumped Irrigation Water (V_p).

Pump Name	Discharge Rate (m^3/s)	Duration (Hrs)	Volume of Pumped Water (m^3)
Pump 1	0.3492	3769	4,738,085.28
Pump 2	0.5287	3743	7,124,126.76
Pump 3	0.425	0	0
Pump 4	0.291	1953	2,045,962.80
Total			13,908,174.84

3.2.2. Computation of the Volume of Water as Effective Rainfall (V_r)

The value of the volume of water received by the irrigation scheme as effective rainfall was obtained by finding the product of the depth of effective rainfall by the total cropped

area of the irrigation scheme. The depth of effective rainfall was calculated using the USDA Soil Conservation method embedded within the CROPWAT 8 software [34]. The computed results are presented in Table 3.

Table 3. Volume of Water as Effective Rainfall (V_r).

Months	Depth of monthly rainfall (mm)	Depth of effective rainfall (mm)	Cropped area in (m^2)	Volume effective rainfall (m^3)
Apr 2022	182.6	129.3	1,833,225.77	237,036.09
May 2022	119.4	96.6	2,986,579.73	288,503.60
Jun 2022	105	87.4	3,642,170.40	318,325.69
Jul 2022	29.5	28.1	5,070,710.57	142,486.97
Aug 2022	69.1	61.5	6,495,203.88	399,455.04
Sept 2022	97.9	82.6	6,470,922.74	534,498.22
Oct 2022	28.9	27.6	5,317,568.78	146,764.90
Nov 2022	121.7	98	4,661,978.11	456,873.85
Dec 2022	115.5	94.2	3,763,576.08	354,528.87
Jan 2023	16.3	15.9	2,339,082.77	37,191.42
Feb 2023	6.1	6	530,138.14	3,180.83
Mar 2023	218.6	142.1	530,138.14	75,332.63
Total				2,994,177.10

3.3. Computation of the Rice Crop Water Productivity (CWP)

The value of the rice crop water productivity was calculated as a ratio of the total mass of crop yield (Mc) obtained by the scheme in a year divided by the total volume of water supplied

(Vs) to the scheme in a year. The value of the rice crop water productivity was computed as shown in Equation (4). The value of the mass of crop production was drawn from Table 1 and volume of water supplied was drawn from Equation (3).

$$\text{CWP} = \frac{5,756,956}{16,902,351.94} = 0.3406 \text{ kg/m}^3 \quad (4)$$

4. Discussion

The rice crop water productivity for the scheme was measured and found to be 0.3406 kg m^{-3} (equivalent of: 2,936 liters of irrigation water used to produce 1kg of rice). This level of rice crop water productivity was low and falls within the typical range reported for continuous flooding irrigation systems ($0.2 - 0.4 \text{ kg m}^{-3}$) [6, 35]. The continuous flooding irrigation systems are generally associated with low crop water productivity compared to the intermittent irrigation systems [36, 37]. The measured value of 0.3406 kg m^{-3} was also lower than that achieved under improved irrigation practices such as the intermittent irrigation method where the rice crop water productivity was reported to range between 0.6 and 1.5 kg m^{-3} [15]. The low rice crop water productivity observed in Ahero Irrigation Scheme was attributed to conveyance losses along the earthen canals and inefficient irrigation water application practices at the field level.

The scheme experienced conveyance losses because there were significant irrigation water losses along the earthen canals. These losses were primarily attributed to the invasion of aquatic weeds and the failing of water control structures along the earthen canals.

The presence of these aquatic weeds in the canal increased the water retention time in the canals leading to higher evaporation losses from the canals' water surface. The prolonged retention time also contributed to the increased percolation losses through the earthen canals' bed. The aquatic weeds in the earthen canals also caused transpiration losses of irrigation water in the canal from their leaves. Similar findings were reported by Elbagoury *et al.* (2025) who observed that aquatic vegetation in open channels significantly reduced the flow velocity thereby decreasing conveyance efficiency [38]. El Noby *et al.* (2020) also found that aquatic vegetation growth along irrigation canals obstructed flow and promoted seepage losses [39]. Ali & Khedr (2018) further demonstrated that the proliferation of aquatic weeds led to substantial water losses through evapotranspiration and infiltration from the channels' bed [40].

The failing water control structures that could not control irrigation water effectively along the canals also reduced the overall conveyance efficiency of the earthen canals. The water control structures were failing because they were aged or vandalised by water users in attempt to abstract more irrigation water than what was allocated. The failed water control structures could not control irrigation water in the canal effectively. A similar study done elsewhere by Awulachew *et al.* (2007) observed that poor maintenance and physical deterioration of irrigation infrastructure reduced the capacity to deliver irrigation water effectively to the irrigated fields [41].

The scheme had low irrigation water application efficiency because of the ineffective continuous flooding irrigation method used to apply water to the crop, poor land preparation, and mismanagement of irrigation water resources by irrigation water users.

The irrigation water application efficiency of the scheme was low because the continuous flooding irrigation regime used by the scheme was not effective causing losses associated with evaporation, surface runoff, seepage, and percolation beyond the root zone. Studies done elsewhere done by Irmak *et al.* (2011) have reported that continuous flooding method led to substantial deep percolation and surface runoff losses [27]. Mo'allim *et al.* (2018) found that prolonged ponding in flooded rice fields increased the vertical movement of water through the soil profile resulting to high percolation losses [42]. LaHue & Linquist (2019) found that flooded rice basins lost appreciable volumes of water via lateral seepage through bunds [43]. Mahindawansa *et al.* (2020) reported that evaporation from ponded water surfaces in irrigated rice basins significantly contributed to overall irrigation water losses [44].

The scheme had low irrigation water application efficiency due to poor land preparation practices. Some of the irrigation basins in the scheme were poorly prepared because they were unlevelled, see Figure 3. The crops in unlevelled irrigation basins experienced water shortages and stress hindering their growth and final production. The unlevelled basins had poor water distribution in them requiring more irrigation water to flood their surfaces. Rogers *et al.* (1997) reported that unlevelled land caused uneven water distribution leading to under-irrigation in some areas and over-irrigation in others which ultimately reduced the yield and irrigation efficiency [45]. Some of the irrigation basins in the scheme had broken bunds, see Figure 4. The poorly constructed basin bunds were thin and susceptible to collapse. The broken basin bunds wasted away the scarce irrigation water resource.

The scheme had low application efficiency because of the mismanagement of irrigation water resource. The farmers mismanaged the resource because the scheme employed a poor method of imposing charges on irrigation water used. The scheme used an area-based pricing method as opposed to volumetric pricing method. The volumetric pricing method encourages efficient water use at the field level [46]. Some farmers mismanaged irrigation water resources by excessively applying water on unlevelled fields and leaving broken bunds unattended leading to unnecessary loss of irrigation water through spillage. Additionally, some water control structures such as sluice gates were vandalised by farmers in attempts to abstract more water than allocated from the canals. This mismanagement was largely due to the absence of volumetric limits on irrigation water to be used by the farmers. Similar findings have been reported in other irrigation schemes where lack of volumetric limits on irrigation water usage resulted to mismanagement of irrigation water resource as reported by Meinzen-Dick (1997) and Molle & Berkoff (2007) [47, 48]. The mismanagement of irrigation water resource was also attributed to the ineffective monitoring and supervision mechanisms employed by the Irrigation Water Users Associations (WUAs) on irrigation water usage. Similar finding has been reported by Ketsela *et al.* (2024) stating

that weak institutional capacity and poor supervision by WUAs led to inefficient water usage [49].



Figure 3. *Unlevelled Irrigation Basin - Water Ponding at the Centre of the Basin while the Perimeter is Dry.*



Figure 4. *Broken Basin Bunds - The Bund Between the Two Basins is Thin and Collapsing.*

5. Conclusion

The measured water productivity of the rice crop in the scheme was 0.3406 kg/m³. The value was low and falls within the typical range for continuous flooding irrigation systems. The value was lower than what is commonly achieved under improved irrigation regimes such as intermittent irrigation. The low productivity was mainly attributed to conveyance losses and losses due to inefficiencies in irrigation water application.

6. Recommendations

The scheme should implement several interventions to improve the rice crop water productivity. The conveyance losses should be reduced by lining the existing earthen canals with an impervious layer. The existing earthen canals should be maintained through regular removal of aquatic weeds and timely repair of the failing water control structures as a cost-effective alternative before undertaking full canal lining. The irrigation water application losses should be minimized by adopting the intermittent irrigation method. The farmers should be trained on proper land preparation techniques. The capacity of the Irrigation Water Users Associations (WUAs) should be strengthened to monitor the utilisation of irrigation water resource to promote accountability.

Abbreviations

AWD	Alternate Wetting and Drying
CWP	Crop Water Productivity
Mc	Mass of Crop Production
Vp	Volume of Pumped Irrigation Water
Vr	Volume of Water as Effective Rainfall
Vs	Volume of Water Supplied
WUAs	Water Users Associations

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Author Contributions

Nickson Kenyoru Marita: Data curation, Formal Analysis, Methodology, Writing – original draft, Writing – review & editing

Emmanuel Chessum Kipkorir: Conceptualization, Formal Analysis, Methodology, Supervision

Joel Kibii: Formal Analysis, Methodology, Supervision

Data Availability Statement

The data is available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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