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An assessment of the Water-Energy-Food nexus in Bidibidi refugee settlement towards the design of sustainable energy technologies

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ABSTRACT

Refugee settlements experience interconnected water, energy, and food (WEF) resource insecurities that are increasingly intensified by climate change, environmental degradation, and declining humanitarian support. However, empirical bottom-up WEF nexus assessments in African refugee contexts remain limited. This study assessed the WEF nexus sustainability and vulnerability dynamics of Bidibidi refugee settlement in Uganda using an integrated bottom-up mixed-methods approach. Household survey data (128 respondents) were combined with 5 focus group discussions, 10 key informant interviews, and 10 in-depth interviews. The Analytic Hierarchy Process (AHP) was applied to quantify WEF nexus sustainability interlinkages, while the Intergovernmental Panel on Climate Change (IPCC)'s exposure, sensitivity, adaptive capacity (ESAc) framework was used to evaluate vulnerability to WEF resource insecurities. The integrated WEF nexus index of 0.1690 classified Bidibidi as marginally sustainable, with strong inequalities across sectors. Water productivity in farming (0.2185) and biomass energy availability (0.1965) were the highest-performing indicators, whereas irrigation water accessibility (0.0238) and food preservation productivity (0.0249) were the weakest. ESAc analysis further revealed intermediate vulnerability across water (0.4996), energy (0.4983), and food (0.4909) insecurities, confirming that vulnerabilities operate as an interconnected system rather than isolated sectoral problems. Findings captured locally experienced resource interactions, coping mechanisms, and community priorities often overlooked in centralized humanitarian planning. Policy and practice should therefore prioritize decentralized solar-powered irrigation, affordable clean cooking systems, community-based briquette enterprises, post-harvest preservation technologies, and participatory governance mechanisms aligned with local capacities. Future research should incorporate longitudinal assessments, seasonal variability, and climate projections on a larger sample size to further strengthen WEF nexus planning and resilience in displacement contexts.

1. Introduction

Uganda hosts over 1.9 million refugees, which implies that it is the 6th largest refugee hosting country in the world [1,2]. Most of the refugees originate from South Sudan and the Democratic Republic of Congo [1–3]. While Uganda's progressive open-door policy has enabled refugee integration, the continued influx of displaced populations has intensified pressure on already constrained water, energy, and food (WEF) resources for both refugees and host communities [4,5]. These pressures are further compounded by climate change, which exacerbates water scarcity, agricultural instability, and energy insecurity through extreme natural hazards and related epidemics [4,6]. Additionally, recent reductions in global humanitarian funding have significantly weakened refugee support systems, thus reducing refugee self-reliance and access to essential services hence increasing vulnerability to poverty, food insecurity, and health risks [7–12]. This has led to a significant impact on the WEF nexus in refugee settlements in Uganda, necessitating that a continuous and deliberate WEF nexus assessment be made to guide policy decisions in management of the refugee situation in Uganda.

The WEF nexus has gained prominence as a holistic, integrated framework for addressing interconnected resource challenges, enhancing policy coherence, and informing sustainable development, especially in relation to the Sustainable Development Goals and climate policy [13,14]. Despite this growing prominence, arguments exist showing that the WEF nexus remains an immature and conceptually unclear framework with limited policy coherence and operational feasibility [15–19]. The nexus concept has increasingly been criticized

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as a policy buzzword whose applications remain largely verbal and expert driven i.e.; (i) it does not adequately disaggregate resource allocation among sectors during political integration because different actors hold varying perceptions and interests, (ii) some private international actors view the concept more as a political economy tool than a scientific framework, using it to advance their own agendas, (iii) the concept being largely shaped by Western knowledge despite its application in specific regions of the Global South, and (iv) governance complexities in decision making, coupled with the lack of consensus on needed guiding principles, which may result in unintended negative impacts on other policy areas like poverty mitigation [15,16]. Many of the desirable goals associated with the nexus are also the main drivers of its criticism, which include focus on centralized governance structures, top-down planning approaches, incoherent policy processes, its failure to account for regional instability, differences in socio-economic conditions, the impact of climate change, situations of resources scarcity, and demographic differences within different contexts. The WEF nexus framework has also further been critiqued for remaining largely conceptual, with unclear uniform definitions and fragmented methods, alongside a tendency toward standardized interpretations that overlook practical complexities, stakeholder dynamics, and context specific challenges across scales and sectors. Key gaps identified in existing WEF nexus studies include incomplete interaction coverage, limited data availability that hinders empirical analysis, inadequate socio-economic stakeholder inclusion, overreliance on top-down governance structures, and a limited ability to capture local level dynamics for contexts like humanitarian settings. For the past decade, empirical studies have examined far fewer resource interactions than theoretical studies[5,14, 20–24]. Different deficiencies and gaps in the assessment and implementation of the WEF nexus include: (i) striking a balance between supply and demand policies/resources, (ii) inability to comprehensively deal with the three-way nexus compared to the two-way approaches i.e. water-energy; food-water, etc., (iii) deriving linkages between the WEF nexus and climate change, sustainable energy technologies, policy direction, (iv) WEF nexus studies' failure to provide concrete information to properly guide decision making in operations to ensure sustainability and promote scalability, and, (v) extremely low levels of local assessment where focus has been on global and national nexuses.

Despite these limitations, there is growing recognition of the need to operationalize the WEF nexus at localized scales using context specific and participatory approaches. In refugee settlements, differences between household level realities and policy level assumptions have been identified as key drivers of intervention failure, particularly in the adoption of sustainable and renewable energy technologies. These discrepancies stem from limited stakeholder participation, gender disparities, and insufficient understanding of local socio-cultural and economic conditions. Recent studies therefore, advocate for bottom-up approaches that capture household level resource interactions and priorities, enabling more inclusive and effective policy design for cases like refugee camps [20–24]. However, such approaches remain underdeveloped, particularly in African refugee contexts, where empirical WEF nexus assessments are very few despite increasing displacement driven by civil conflicts, climate change, and resource competition [25–28].

Existing WEF nexus studies in refugee and humanitarian settings are predominantly focussed on the Middle East and Asia, with limited representation of studies from Africa. These studies largely adopt top-down WEF assessment approaches, focusing on macro level resource flows while neglecting micro level interactions and stakeholder engagement [22,29,30]. Studies in Jordan and Lebanon have highlighted increasing water stress and energy demand due to refugee influx, as well as the potential of renewable energy to mitigate trade-offs within the nexus [31–35]. While these studies provide valuable insights, they often remain sector-fragmented, focussing on dual interactions rather than integrated system dynamics. Moreover, they rarely translate nexus assessments into practical design and policy recommendations tailored to local conditions. This gap underscores the need for bottom-up household approach which has been reported successful in capturing the complexity of WEF interactions at local level hence significantly informing policy decisions. A bottom-up household approach to the WEF nexus resulted in inclusive policy development and increased awareness related to renewable energy technologies and climate change. The prioritization of household demand management and understanding user consumption patterns of water, energy and food, was observed to have significant potential in informing policy decisions, when compared to a macro-level supply side approach typically used in WEF nexus studies. This approach also captured gender related differences at household level in decision making on WEF related practices [22]. Refugee settlements present unique characteristics that fundamentally shape WEF interlinkages, including their semi-permanent nature, dependence on humanitarian aid, limited resource ownership, and dynamic population structures [36,37]. These factors influence resource access, utilization, and governance in ways that differ significantly from conventional rural and urban systems. For example, insecure land tenure can limit arable farming, while fluctuating aid flows can disrupt access to food and energy resources. Additionally, the design and location of refugee settlements often place them in environmentally disadvantaged areas, further intensifying resource pressures and vulnerability [38,39]. These contextual dynamics necessitate analytical approaches that explicitly account for the socio-economic, political and environmental dimensions of displacement settings.

In response to these gaps, this study adopted a bottom-up, mixed-methods approach to assess the WEF nexus in Bidibidi Refugee Settlement. It integrated household level survey data with qualitative insights to quantify resource interlinkages, assess vulnerabilities, and inform technology design. Specifically, the study aimed to use empirical findings for: (i) defining WEF nexus sustainability indicators and applying the Analytic Hierarchy Process (AHP) to obtain composite indices that can explain the relationships between water, energy, and food resources of Bidibidi refugee settlement, (ii) assessing the level of exposure, sensitivity, and adaptive capacity (ESAc) to WEF resource insecurities using Intergovernmental Panel on Climate Change (IPCC)'s framework and define the existing interactions between such vulnerabilities, and (iii) defining the policy and technology design implications to bridge the gap between WEF nexus assessment and practical implementation for a refugee setting. This study contributes to advancing empirical WEF nexus research tailored to refugee settings. By integrating resource nexus quantification, and vulnerability assessment within a bottom-up approach, it moves beyond descriptive analysis towards actionable insights. The findings are expected to inform more inclusive governance strategies and context-appropriate technological interventions, that support sustainable resource management in displacement contexts.

2. Methodology

2.1. Case study

Bidibidi was the refugee study site used as in Fig. 1. The settlement is approximately 800 km^2 and is the largest refugee settlement in Uganda with over 230,000 people [40,41]. It is in the northwestern part of Uganda situated in Yumbe district. Fig. 1 shows the five zones (1 – 5) that make up Bidibidi refugee settlement. Majority of refugees originate from South Sudan due to clashes and the main livelihood source is subsistence farming [40].

2.2. Study design

A concurrent mixed methods approach was followed involving both quantitative and qualitative techniques i.e., a cross-sectional household survey supported by case study interactions. Simple random sampling was used for the survey whereas purposive sampling was applied to person interactions. Vulnerable people like disabled and under-age 18 individuals were discriminated from the sample to accord with ethical

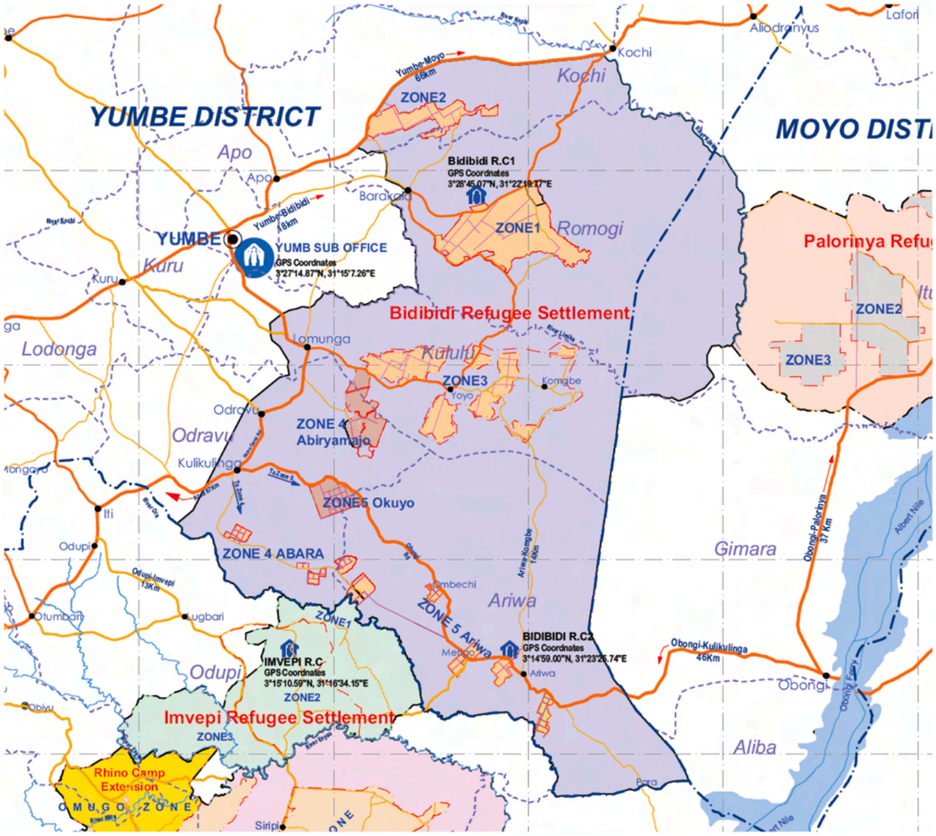

Fig. 1. An extract of the map of Bidibidi refugee settlement showing the different zones (Source: UNHCR 2018) [43].

guidelines approved under this study protocol. With total population of Bidibidi approximated at 230,000, Slovin's formula in Eq. (1) was used to calculate the sample size of 399 for the survey [41,42]. However, due to logistical and time constraints, a sample size of 128 individual households was used.

$$n = \frac{N}{1 + N(e)^2} \tag{1}$$

$$n = \frac{230000}{1 + 230000(0.05)^2}$$

$$n = 399$$

Where n is sample size, N is target population, and e is standard error.

Data collection involved using semi-structured questionnaires (128 respondents) for surveys, focus group discussions (FGDs) of 35 participants, 10 key informant interviews (KIIs) and 10 in-depth interviews (IDIs) for person-contact interactions. The data collection was done in three zones to represent the settlement with a criterion that majority of the sampled individuals had at least travelled and obtained knowledge about zone 1 and 2. For the survey, zone 3 had 38% of respondents, zone 4 (23%) and zone 5 (39%). Although Slovin's formula gave a recommended sample size of 399 respondents, logistical and time limitations constrained the final survey sample size to 128 individual households. This limits generalizability to the whole Bidibidi population and may potentially cause bias to a given extent. However, triangulation with FGDs, KIIs, and IDIs helped strengthen contextual reliability and interpretation of findings. Future related studies should use a larger sample size across all the settlement's zones.

2.3. Selection of WEF nexus sustainability indicators

Sustainability has been referred to as use of natural resources ethically, equitably, and efficiently to fulfill current and future generation needs. It is centered on maintenance capacity for ecological systems to improve social systems quality [44,45]. The WEF nexus is very helpful in assessing interlinkages between water, energy, and food systems, enabling understanding of trade-offs and synergies to ensure resource security and sustainability of the ecosystem [46,47]. Assessment of the WEF nexus in this study began by defining the sustainability indicators from the survey data. This was in relation to the key drivers associated with resource security i.e., availability, accessibility, self-sufficiency, and productivity [46,47]. Table 1 shows the WEF nexus sustainability indicators and their values, which were computed using weighted average of variables under each indicator per sector using Eq. (2) [48]. Weights were assigned to frequency counts of each variable basing on its relative importance to the indicator in line with the literature. water access in Bidibidi was observed to be sourced from motorized systems (43%), followed by hand pumps (30%); livelihoods mainly rely on rain-fed agriculture and solarized boreholes for small scale vegetable gardening, a transition from water streams [49–51]. A rapid fuel assessment revealed that 97% of refugee households used only fuelwood for cooking compared to 3% of charcoal [52]. An energy for households uses desk review further discovered that most refugees in Bidibidi used a 10 W pico-PV solar system to light up 3 to 4 bulbs, charge their phones and radios [53]. A study of South Sudan refugees in Imvepi settlement revealed that most dominant staple foods were cassava, maize, beans, sorghum, simsim and different vegetables [54]. A similar pattern was observed in FGDs, KIIs and IDIs where; key water sources were motorized solar tap water systems and boreholes, main livelihood was farming dealing in cassava, maize, beans, and vegetable crops, majority used firewood for cooking, and 10 W solar PV panel was the most common source of electric energy for lighting and charging radios. The main

Table 1
WEF nexus sustainability indicators for Bidibidi refugee settlement.

Sector	Sustainability indicator	Variables	Frequency counts (f_i)	Assigned weights (w_i)	Indicator value (f)
Water	Proportion of households having water access (availability)	Motorized solar tap water supply	31	0.50	30.60
		Water streams	19	0.15	
		Boreholes	35	0.35	
		Total	85	1.00	
	Proportion of households using irrigation for crop production (accessibility)	Rain water	18	0.35	11.67
		Watering cans	31	0,07	
		Borehole water	10	0.26	
		Jerrycans	1	0.03	
		Water bottles	1	0.01	
		Water streams	2	0.28	
		Total	63	1.00	
	Proportion of households engaged in crop production (productivity)	Farming	118	1.00	118.00
		Total	118	1.00	
Energy	Proportion of households using biomass energy (availability)	Firewood	120	0.80	96.90
		Charcoal	5	0.15	
		Briquettes	3	0.05	
		Total	128	1.00	
	Proportion of households using multiple fuel sources – energy diversification (self-sufficiency)	Firewood	120	0.80	96.90
		Charcoal	5	0.15	
		Briquettes	3	0.05	
		Total	128	1.00	
	Proportion of households using solar powered appliances (self-sufficiency)	Cell phones	20	0.25	20.30
		Computers	3	0.01	
		Solar cooker	8	0.03	
		Refrigerators	4	0.05	
		Light bulbs	27	0.40	
		Radios	16	0.25	
		TV	3	0.01	
		Total	81	1.00	
	Proportion of people using energy for productive purposes (productivity)	Grinding mill using diesel fuel	86	1.00	86.00
		Total	86	1.00	
Food	Proportion of households practicing own food production (self-sufficiency)	Beans	19	0.15	22.07
		Cassava	22	0.30	
		Greens	16	0.25	
		Maize	38	0.22	
		Simsim	1	0.01	
		Gnuts	2	0.02	
		Cowpeas	1	0.01	
		Sorghum	5	0.04	
		Total	104	1.00	
	Proportion of households using food preservation methods (productivity)	Granary	11	0.10	12.80
		Sun drying	15	0.70	
		Smoking	6	0.20	
		Total	32	1.00	

water sources, livelihood, cooking fuel, productive energy use, and staple foods of Bidibidi have been shown from Figs. 2–6 respectively.

$$\widetilde{f} = \frac{\sum_{i=1}^{n} w_i f_i}{\sum_{i=1}^{n} w_i} \tag{2}$$

where w_i is the weight related to the frequency count value f_i of the variable and $\widetilde{f}$ is the average weighted value for the sustainability indicator.

2.4. Application of AHP on the WEF nexus sustainability indicators

The Analytic Hierarchy Process (AHP) was the multi criteria decision-making analysis method used to numerically understand the relationship and interlinkage between water, energy, and food resources of Bidibidi. AHP, developed by Thomas L. Saaty, is a decision-making method that helps assign priorities by doing pair comparisons to form a matrix. Each pair is evaluated using a scale from 1/9 to 9, where higher values indicate greater importance of row factor over column factor, and equal importance is rated as 1. Lower values (1/3 to 1/9) indicate weaker relationships. A score of 9 means that the row indicator is far more important than the column indicator it is compared to, while 1/9 means it is far less important. In the WEF nexus context, the method helped determine an indicator's weights based on its relative influence compared to other indicators [55–57].

2.4.1. Pairwise comparison matrix (PCM) for WEF nexus sustainability indicators of Bidibidi

Indicator ratios for the WEF nexus sustainability indicators using their indicator values i.e., row (i)/column (j) were mapped onto Saaty's discrete scale of 1–9 to form a 9 × 9 pairwise comparison matrix. Rounding off the indicator ratio values greater than 1 was done such that they are close to 1–9 whole number scale, while the reciprocal of these ratio values was used whenever the row (i) and column (j) indicator values were interchanged. 1 represented equal importance, 3 being moderate, 5–strong, 7–very strong, and 9–of extreme importance [58]. This was the basis of scaling used amongst the relationships. The pairwise comparison judgments used for constructing the PCM in this study were developed using empirically obtained indicator ratios got from the calculated sustainability indicator values using survey results, supported by literature evidence. The PCM showing the relationship amongst the Bidibidi WEF nexus sustainability indicators is shown in Table 2.

Fig. 2. Sources of water access: (a) Water stream; (b) Tap stand point; (c) Main diesel-solar hybrid station of the motorized solar tap water supply system; (d) 10,000 to 112,000 litres water reservoir tank for the motorized water supply system.

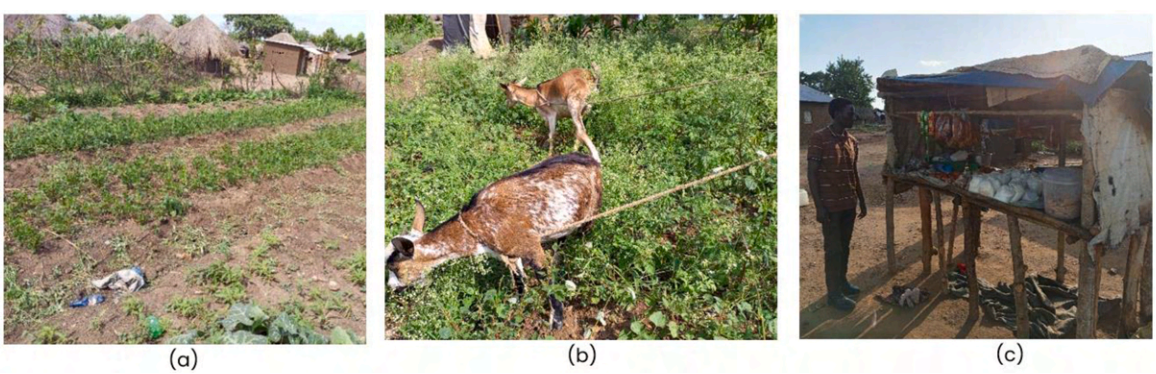

Fig. 3. Main livelihood in Bidibidi: (a) Crop rearing under farming; (b) Goat rearing under farming; (c) retail business selling farm produce.

2.4.2. Normalization of the pairwise comparison matrix for WEF nexus sustainability indicators

The obtained PCM for the WEF nexus sustainability indicators was normalized using equation Eq. (3) [59]. The normalized PCM is shown in Table 4 where summation of indices per column is always 1 [46].

$$N_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \tag{3}$$

Where N is PCM of n x n order, i = 1, 2, 3,…..n, and j = 1, 2, 3,…..n.

The priority vector was obtained by finding the row averages for the normalized PCM of the WEF nexus sustainability indicators so as to get their composite indices as shown in Table 5 [59]. Consistency of the derived indices is always tested during the AHP analysis to ensure that the consistency ratio (CR) is <0.1 [60]. Consistency of the normalized PCM was tested using equations Eq. (4) and (5) and was found to be 0.0042 which is acceptable. Although the AHP consistency ratio was within acceptable limits, a detailed sensitivity analysis of PCM was not conducted because this study constructed the PCM from empirically obtained indicator ratios based on survey data. Therefore, the obtained weights mainly show observed quantitative relationships rather than aggregated expert judgements and group consensuses which are very important when using sensitivity analysis to address user disparities in AHP [61].

$$CR = \frac{CI}{RI} \tag{4}$$

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{5}$$

Where CI is consistency index, λ_{max} is the principal eigenvalue, RI is

Fig. 4. Main cooking fuel: (a) Firewood; (b) Charcoal; (c) Briquette.

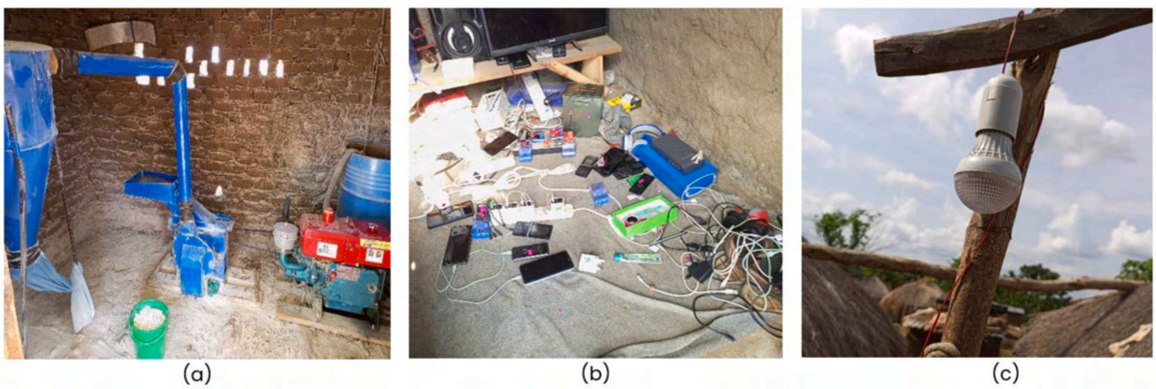

Fig. 5. Productive energy usage: (a) Grinding mill using diesel fuel; (b) Phone charging station; (c) Light bulb.

Fig. 6. Staple foods: (a) Cassava flour; (b) Greens; (c) Beans.

the random index basing on the matrix order with number of criteria, n for every pairwise comparison [56].

The WEF nexus integrated index for Bidibidi refugee settlement was obtained as 0.1690 by calculating the weighted average of the composite indices seen in Table 5 [46]. Indices were ranked according to weight with 9 being highest ranked and 1 being lowest ranked. Using a classification scale of 0 to 1 to represent unsustainable and highly sustainable resource management respectively as in a South Africa case study, the obtained WEF nexus integrated index of Bidibidi is taken to be marginally sustainable [46].

2.5. *Vulnerability assessment of WEF insecurities for Bidibidi*

Vulnerability has been understood as susceptibility of systems to disturbances shaped by social, economic, physical, and environmental conditions, emerging from interactions between exposure, sensitivity, and adaptation. It is observed as a dimension of risk and impacts of hazards [62–64]. Water, energy, and food systems have always been known to be vulnerable in the resources perspective. This study used the Intergovernmental Panel on Climate Change (IPCC)'s framework particularly the fourth assessment report to define vulnerability as a function of exposure (E), sensitivity (S), and adaptive capacity (Ac) for the water-energy-food (WEF) resource insecurities of Bidibidi refugee

Table 2
Pairwise comparison matrix of the WEF nexus sustainability indicators.

Indicator	Water Sources Availability	Irrigation Water Accessibility	Water Productivity in Farming	Biomass Energy Availability	Cooking Energy Diversification	Solar Energy Self-sufficiency	Energy Productivity	Food Production Self-sufficiency	Food Productivity in Preservation
Water Sources Availability	1	3	1/4	1/3	1/3	2	1/3	1	2
Irrigation Water Accessibility	1/3	1	1/9	1/8	1/8	1/2	1/7	1/2	1
Water Productivity in Farming	4	9	1	1	1	6	1	5	9
Biomass Energy Availability	3	8	1	1	1	5	1	4	8
Cooking Energy Diversification	3	8	1	1	1	5	1	4	8
Solar Energy Self-sufficiency	1/2	2	1/6	1/5	1/5	1	1/4	1	2
Energy Productivity	3	7	1	1	1	4	1	4	7
Food Production Self-sufficiency	1	2	1/5	1/4	1/4	1	1/4	1	2
Food Productivity in Preservation	1/2	1	1/9	1/8	1/8	1/2	1/7	1/2	1

settlement [65]. Vulnerability was assessed using an indicator-based approach[66].

2.5.1. Identification of vulnerability indicators for WEF insecurities of Bidibidi

Vulnerability assessment of the WEF insecurities began by defining the vulnerability indicators from the survey data. This was in relation to the dimensions of exposure (threats from hazards), sensitivity (extent to which the system is influenced by being exposed), and adaptive capacity (system's ability to adjust and cope with the risks and hazards being exposed to). For adaptive capacity, indicators were identified as physical capital (PC), financial capital (FC), human capital (HC), and social capital (SC) assets [66]. Table 3 shows the vulnerability indicators and their values, which were computed by dividing the frequency counts of each variable by its valid responses respective of the indicator, dimension, and sector insecurity.

2.5.2. Min-max normalization of vulnerability indicators

Vulnerability indicator values were normalized using the maxima-minima method which has been used in a number of studies [66–68]. Eq. (6) is the formula that was used for normalization of the indicators to obtain indices running from 0 – 1 (indicative of low and extreme vulnerability respectively) [67].

$$NV_i = \frac{X_i - X_{min}}{X_{max} - X_{min}} \tag{6}$$

Where NV_i is normalized indicator value, $X_i$is proportional value for vulnerability indicator, X_{min} and X_{max} is the minimum and maximum value respectively for the indicators within a given dimension group of the same insecurity sector. The normalized values for the vulnerability indicators are shown in Table 3.

2.5.3. Aggregating the indicators to form the vulnerability index

The composite scores for each exposure, sensitivity, and adaptive capacity dimension within an insecurity sector was obtained as the arithmetic mean of all normalized indicator values belonging to that dimension. The scores were then used to compute the vulnerability index (Vi) for each sector using Eq. (7) [67]. In the equation, adaptive capacity is computed as $(1 - A_c)$ so as to make sure only vulnerability contribution is captured.

$$Vi = \frac{E_i + S_i + (1 - Ac_i)}{3} \tag{7}$$

Where Vi is the vulnerability index of WEF insecurity, i, E_i, S_i, and Ac_i are exposure, sensitivity, and adaptive capacity to the WEF insecurity respectively.

2.6. Ethical considerations

Ethical approval was obtained from both the Makerere University School of Social Sciences Research and Ethics Committee (MAKSS REC 08.2024.776) and the Uganda National Council for Science and Technology (SIR416ES).

3. Results and discussion

3.1. Performance of WEF nexus sustainability indicators for Bidibidi

The composite indices are shown in Table 5. Table 5 showed significant differences in sustainability performance across the water, energy, and food sectors in Bidibidi refugee settlement. The indices were mapped on a spider graph (see Fig. 7) so as to clearly visualize the interlinkage among the WEF sectors in terms of their sustainability indicators. If an indicator is further away from central axis, the greater the sustainability, and if it is closer to the axis, the greater the unsustainability [46]. The overall WEF nexus integrated index of 0.1690 places

Table 3
Vulnerability indicators for the WEF insecurities of Bidibidi refugee settlement.

Sector Insecurity	Dimension	Vulnerability Indicator	Variable	Frequency counts (f)	Total valid responses	Indicator proportional value	Normalized value
Water Insecurity	Exposure	Distant water sources	Long distance for fetching water	23	45	0.511	1.0
		Droughts and seasonal streams	Drought	3	45	0.066	0.0
	Sensitivity	Water scarcity	Scarcity of water	12	45	0.266	1.0
		Time consumption	Wastage of time	1	45	0.022	0.0
	Adaptive Capacity	Access to motorized solar tap water supply (PC)	Motorized solar tap water supply	19	85	0.224	0.0
		Technical skill in repairing solar water pumps (HC)	Experience in Repairing Solar Systems/Water Pumps	43	117	0.367	0.5035
		Access to watering cans and jerrycans (PC)	Watering cans and jerrycans	32	63	0.508	1.0
Energy Insecurity	Exposure	Distant firewood fuel collection sources	Long distances	45	58	0.776	0.8228
		Dominant reliance on firewood cooking fuel	Firewood	120	128	0.9375	1.0
		Weather changes	Rain that makes fuel wet	2	78	0.026	0.0
		Physical safety risk during fuel collection	Rape and threat from land lords	3	58	0.052	0.0285
	Sensitivity	Scarcity of firewood fuel	Scarcity of firewood	33	78	0.423	0.2722
		Unhealthy smoke exposure	Too much smoke	22	78	0.282	0.0
		Use of inefficient 3-stone cook stove	3 Stone wood stove	96	120	0.800	1.0
	Adaptive Capacity	Access to solar cook stoves (PC)	Electric stove	8	81	0.099	0.0918
		Access to briquettes (PC)	Briquettes stove	4	120	0.033	0.0
		Willingness to adopt installment pre-payment (FC)	Payment in instalments	24	64	0.375	0.4757
		Local membership initiatives (SC)	Yes to membership	85	113	0.752	1.0
Food Insecurity	Exposure	Dominant reliance on rainfed agriculture	Rain water	18	63	0.286	0.1769
		High fuel consumption staple (beans)	Meal that mostly finish fuel (beans)	31	41	0.756	1.0
		Inadequate storage facilities	Poor storage facilities	15	81	0.185	0.0
	Sensitivity	Low meal frequency	One meal per day	36	117	0.308	0.8239
		Food spoilage	Food gets spoilt	6	81	0.074	0.0
		Attack from pests	Rats	29	81	0.358	1.0
	Adaptive Capacity	Access to mini-solar powered irrigation (PC)	Solar-powered irrigation	51	109	0.468	0.5824
		Diversification of income sources (FC)	Livelihood	5	69	0.072	0.0
		Local membership initiatives (SC)	Yes to membership	85	113	0.752	1.0

the settlement within the "marginally sustainable" category based on the classification framework of Nhamo et al. [46]. However, intra-sector inequalities existed, particularly within the water–food interface.

The water sector exhibited the widest difference of indicator performance among all nexus components. water productivity in farming recorded the highest index (0.2185), classified as moderately sustainable, whereas irrigation water accessibility registered the lowest index (0.0238), classified as unsustainable. This big difference demonstrates that agricultural production in Bidibidi remains heavily dependent on seasonal rainfall rather than on structured irrigation systems. Although households actively participate in farming activities, productive water infrastructure remains extremely limited. This was the case in 90% of KIIs, 70% of IDIs, 27% of FGDs where rain-fed farming was the main livelihood. Water sources availability (0.0624) also fell within the unsustainable category and remained substantially below the integrated WEF index. This suggests that existing humanitarian water interventions have not yet fully achieved reliable and sufficient water access relative to population demand. Despite investments in handpumps and communal motorized water systems by humanitarian agencies and government actors, irregular supply and water scarcity prevails as is in neighbouring camp, Rhino due to reliance on solar-powered pumping [69,70]. Related observations were reported by Sonja et al. [71], who identified refugee settlements in Uganda to be located in areas exposed to high temperatures and low levels of rainfall. The results further support findings by Wanyama et al. [72], who grouped Uganda under inadequate national irrigation capacity due to insufficient water access which constrains agricultural productivity. The observed contrast between relatively high rainfed farming productivity and extremely low irrigation water accessibility reflects a broader structural imbalance in refugee agricultural systems. Water provision strategies in arid humanitarian settlements like Za'atari of Jordan primarily prioritize domestic consumption over use for agricultural production [73]. Therefore, farming systems remain highly vulnerable to rainfall variability, thereby constraining resilience and long-term food self-sufficiency.

In the energy sector, biomass energy availability and cooking energy diversification both at 0.1965 were jointly ranked among the highest indicators overall and fell within the marginally sustainable category. Energy productivity (0.1866) also indicated a considerable use of energy for agro-processing and small-scale income generation. FGDs, KIIs, and IDIs as well reported thorough firewood reliance greater than 94.6% and dominance of cassava diesel grinding mills (40–90%). These findings are consistent with studies across refugee settlements in Uganda, where woodfuel biomass remains the dominant household energy source for cooking [52,74,75]. However, solar energy self-sufficiency recorded a very low index value of 0.0422 (see Table 5) and remained within the unsustainable category. The result demonstrates that full capacity reliance on modern renewable energy technologies within Bidibidi remains

Table 4
Normalized pairwise comparison matrix.

Indicator	Water Sources Availability	Irrigation Water Accessibility	Water Productivity in Farming	Biomass Energy Availability	Cooking Energy Diversification	Solar Energy Self-sufficiency	Energy Productivity	Food Production Self-sufficiency	Food Productivity in Preservation
Water Sources Availability	0.0612	0.0732	0.0517	0.0662	0.0662	0.0800	0.0651	0.0476	0.0500
Irrigation Water Accessibility	0.0204	0.0244	0.0230	0.0248	0.0248	0.0200	0.0279	0.0238	0.0250
Water Productivity in Farming	0.2449	0.2195	0.2067	0.1987	0.1987	0.2400	0.1953	0.2381	0.2250
Biomass Energy Availability	0.1837	0.1951	0.2067	0.1987	0.1987	0.2000	0.1953	0.1905	0.2000
Cooking Energy Diversification	0.1837	0.1951	0.2067	0.1987	0.1987	0.2000	0.1953	0.1905	0.2000
Solar Energy Self-sufficiency	0.0306	0.0488	0.0344	0.0397	0.0397	0.0400	0.0488	0.0476	0.0500
Energy Productivity	0.1837	0.1707	0.2067	0.1987	0.1987	0.1600	0.1953	0.1905	0.1750
Food Production Self-sufficiency	0.0612	0.0488	0.0413	0.0497	0.0497	0.0400	0.0488	0.0476	0.0500
Food Productivity in Preservation	0.0306	0.0244	0.0230	0.0248	0.0248	0.0200	0.0279	0.0238	0.0250

Table 5
Composite indices of the WEF nexus sustainability indicators for Bidibidi.

Indicator	Sector	Composite Index	Rank	Classification
Water Productivity in Farming	Water	0.2185	9	Moderately Sustainable
Cooking Energy Diversification Self-Sufficiency	Energy	0.1965	7	Marginally Sustainable
Biomass Energy Availability	Energy	0.1965	7	Marginally Sustainable
Energy Productivity	Energy	0.1866	6	Marginally Sustainable
Water Sources Availability	Water	0.0624	5	Unsustainable
Food Production Self-Sufficiency	Food	0.0486	4	Unsustainable
Solar Energy Self-Sufficiency	Energy	0.0422	3	Unsustainable
Food Productivity in Preservation	Food	0.0249	2	Unsustainable
Irrigation Water Accessibility	Water	0.0238	1	Unsustainable
CR = 0.0042		$\sum = 1$		
WEF nexus integrated index (weighted average)		0.1690		

minimal despite international commitments toward clean energy transitions in humanitarian contexts. The community has been reported to majorly rely on a 10 W PV solar system [53]. This was the case in qualitative results of this study. Comparable findings reported by Rosenberg-Jansen [76] and Maalim et al. [77], identify insufficient energy resources, and affordability limitations as major barriers to solar energy adoption in refugee settlements. Importantly, the relatively high energy performance should not be interpreted as evidence of long-term sustainability. The dominance of biomass energy reflects dependence on environmentally unsustainable fuel pathways associated with deforestation and degradation of surrounding communal ecosystems [40,41, 78]. The apparent strength of the energy sector therefore masks an underlying nexus trade-off in which energy security is achieved at significant environmental cost.

The food sector recorded the weakest sustainability performance, with all indicators classified as unsustainable. food production self-sufficiency achieved an index value of 0.0486, while food productivity in preservation recorded 0.0249. These findings identify food security as the most critical vulnerability within the Bidibidi WEF system. The low food production self-sufficiency index reflects structural limitations associated with land access and agricultural productivity. Although Uganda's refugee policy framework freely allows small plots cultivation for refugee households, available land-based approach is insufficient to support household-level food self-reliance [79–81]. In addition, increasing pressure on arable land between refugee and host populations intensifies seasonal food insecurity and constrains agricultural expansion e.g., Nagujja et al. [82], reported 25% insecure land access amongst refugees and 70% tenure insecurity amongst host communities to cause livelihood insecurities in northern Uganda. Food productivity in preservation emerged as one of the weakest indicators across the entire nexus system (see Table 5). The low index indicates minimal household engagement in post-harvest preservation practices besides sun-drying as observed in 24.3% of FGDs, 40% of KIIs, and 80% of IDIs. This finding aligns with Garsow et al. [83], who reported minimal food storage ways in refugee camps hence contributing to diseases. From a nexus perspective, the result reflects inefficiency within the food system since agricultural outputs are not effectively retained and processed to full capacity.

The integrated WEF Nexus Index of 0.1690 further demonstrates that Bidibidi's sustainability performance remains constrained by interconnected sectoral deficits rather than isolated resource shortages. The strongest nexus interaction emerged within the water–food relationship,

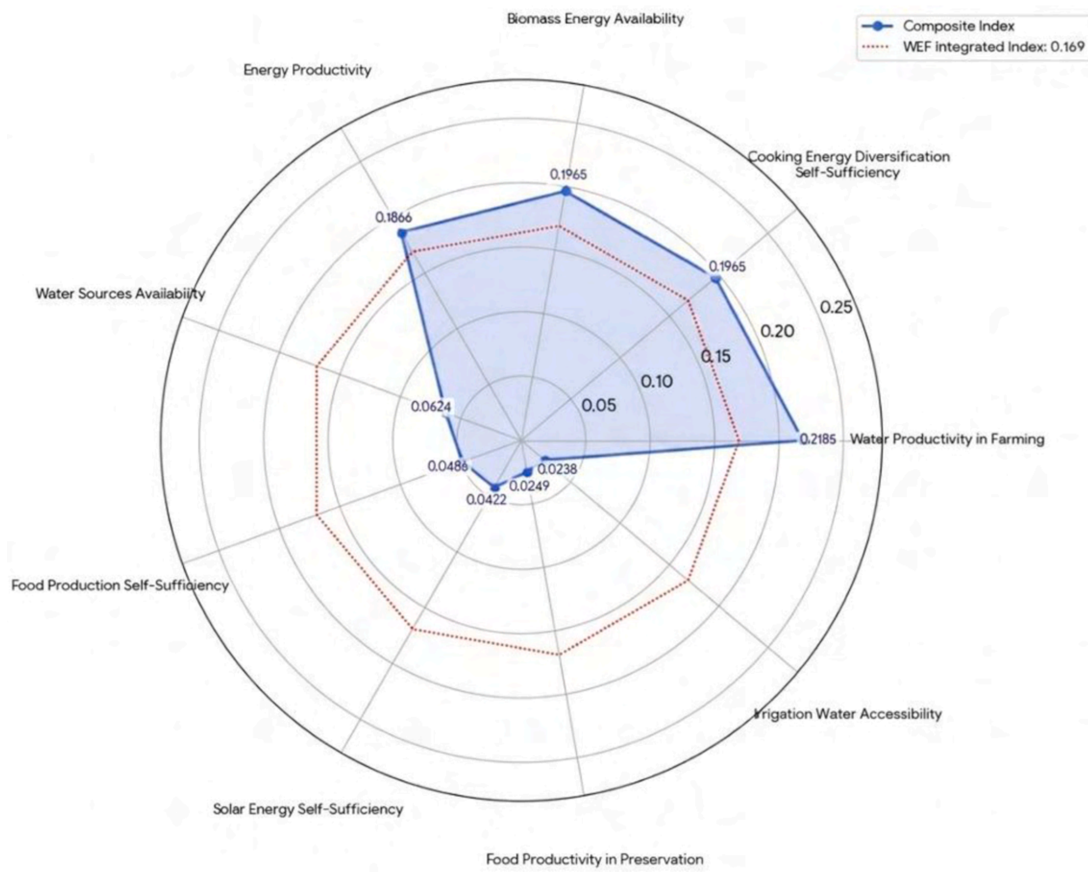

Fig. 7. Performance of WEF nexus sustainability indicators for Bidibidi refugee settlement.

where extremely low irrigation accessibility directly limits agricultural productivity and food self-sufficiency. In Pakistan, water scarcity was reported to result into low farm yields and household income thus food insecurity [84]. The issue of water scarcity has similarly been pointed out as one of the most common energy nexus related challenges in Africa's agricultural systems [85]. Governing the water resource is very important in ensuring a multi-faceted management of the WEF nexus [86]. Expanding borehole-based solar-powered pumping systems to supply smallholder irrigation and domestic use can help generate simultaneous improvements in both water and food sector performance for the settlement. Ground water availability has been reported to be sufficient for household demand despite 90% of the settlement being in a low potential access area [49].

Similarly, the energy–food nexus revealed important trade-offs. High biomass dependence supports household energy access but accelerates deforestation, land degradation, and ecological stress within the settlement and its host community [40,41,78]. Addressing this challenge requires integrated interventions that combine affordable clean cooking technologies, renewable energy expansion, and sustainable land management approaches. Most refugee respondents indicated an unwillingness to pay above 500 Ugandan shillings (UGX) monthly for technologies, therefore, using high density briquettes with efficient stoves, and planting of fast-growing, locally adaptable trees, is a feasible option [82,83]. This is because biomass remains dominant in rural refugee camps due to under developed markets, making improved cookstoves the most viable intervention. Liquefied Petroleum Gas (LPG) and electric pressure cookers have succeeded in urban refugee settings like Bangladesh but are constrained in off-grid settings by high costs, unreliable power supply, and subsidy-induced market distortions [87]. Fast-growing species like *Eucalyptus grandis, Senna siamea*, and *Calliandra calothyrsus* have been highlighted to support sustainable fuel regeneration and reduce deforestation pressure in northern Uganda [88]. Sustainable resource-production systems like use of renewables were highlighted to be very important in minimizing trade-offs in a COVID-19 prone WEF system [89]. Finally, the low food preservation index highlights a missed opportunity within the energy–food nexus because productive energy applications can be redirected toward post-harvest processing and storage technologies capable of simultaneously strengthening food retention and household livelihoods.

The system complexity and interconnection identified between WEF resources of Bidibidi refugee settlement was further visually arranged in a framework that can be seen in Fig. 8. The framework shows independence between the resource sectors i.e., water enabling solar pumping from boreholes, cooking food, and crop irrigation, while solar energy is required for food drying, and water abstraction to be used for both domestic and irrigation purposes. Chemical energy in terms of diesel fuel and biomass (firewood and briquettes) is respectively used for milling dried cassava and cooking the obtained cassava flour. Processed cassava from drying to flour can be seen in Fig. 9. The food system provides biomass fuels like maize stalks to be carbonized and used for briquette making, and as well influences water use by dominantly using drought resistant crops like cassava. These interconnections are shaped by policies and institutional governance starting from Office of the Prime Minister (OPM), hazards like droughts, and pressures from climate change, environmental degradation and eco-system destruction. The highlight from this is that managing one resource inevitably affects the availability, access, productivity and sustainability of the others.

3.2. Exposure, sensitivity, and adaptive capacity to WEF insecurities in Bidibidi

The ESAc analysis revealed that vulnerability to water, energy, and

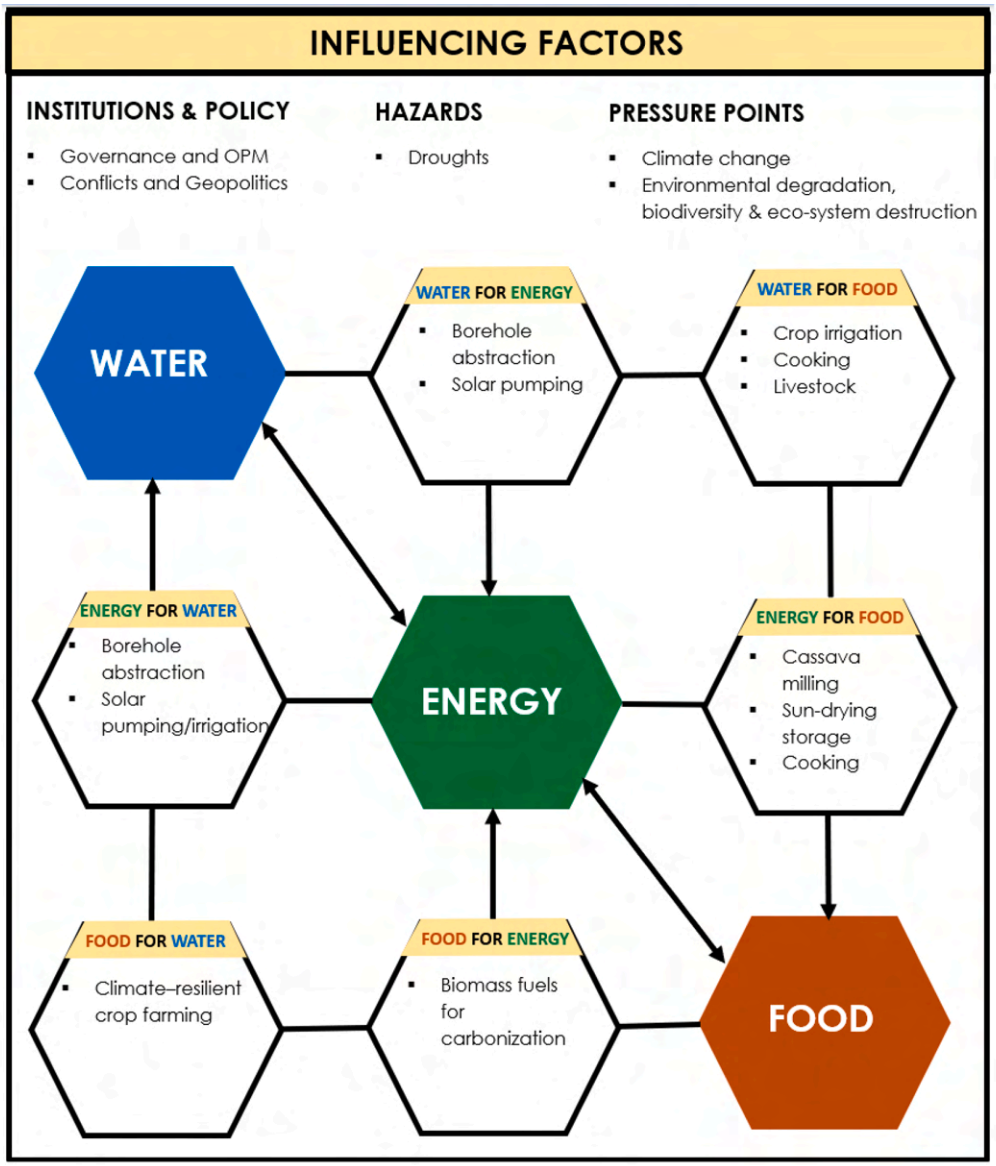

Fig. 8. WEF nexus framework.

Fig. 9. Cassava processing: (a) Sun drying; (b) Dried particles of cassava ready for milling; (c) Cassava flour packed in sacks after milling.

food insecurities in Bidibidi generally occurs as a system, with all three sectors falling within the intermediate vulnerability classification range. The classification used was according to Ngarava [67] i.e., low ranging from 0.00 to 0.20, moderate (0.21–0.40), intermediate (0.41–0.60), high (0.61–0.80), and extreme (0.81–1.00). Water insecurity recorded the highest Vulnerability Index (Vi = 0.4996), followed closely by energy insecurity (Vi = 0.4983) and food insecurity (Vi = 0.4909) as shown in Table 6. The narrow variation seen across the sectors in Fig. 10

Table 6
Exposure, sensitivity, and adaptive capacity composite scores and vulnerability index of WEF insecurities in Bidibidi.

Sector insecurity	Exposure (E)	Sensitivity (S)	Adaptive capacity (Ac)	Vulnerability index (Vi)	Classification
Water insecurity	0.500	0.500	0.501	0.4996	Intermediate
Energy insecurity	0.463	0.424	0.392	0.4983	Intermediate
Food insecurity	0.392	0.608	0.528	0.4909	Intermediate
Overall vulnerability index (average)				0.4963	Intermediate

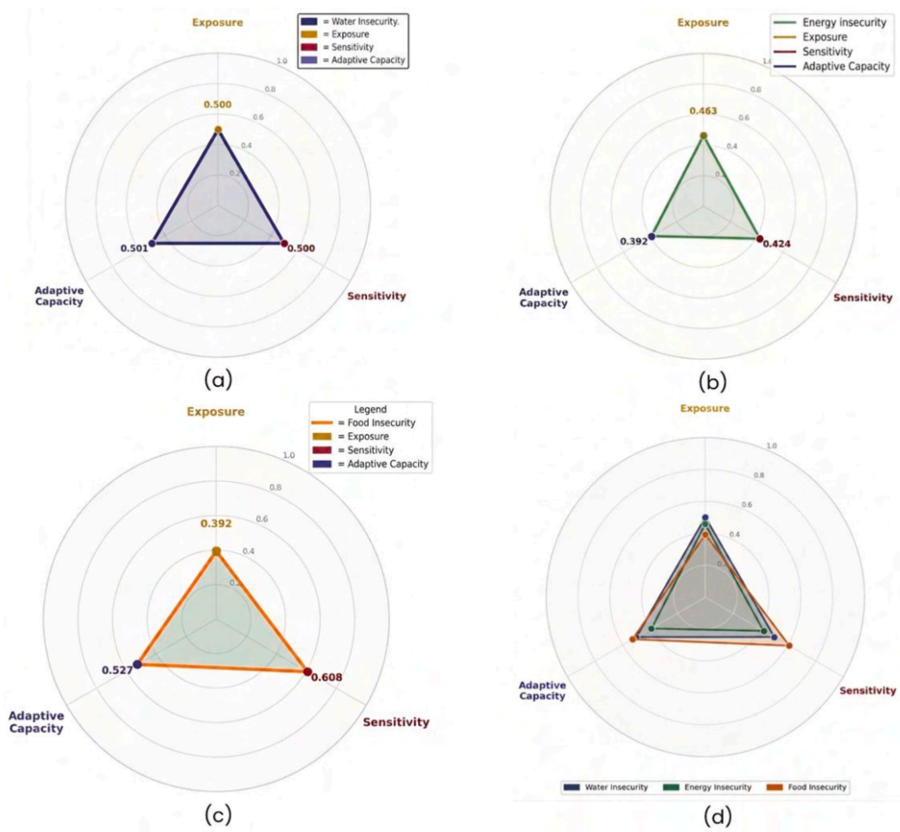

Fig. 10. Radar chart visualization of exposure, sensitivity, and adaptive capacity for: (a) Water insecurity; (b) Energy insecurity; (c) Food insecurity; (d) Combined WEF insecurities.

indicates that vulnerability within the settlement is not confined to a single resource domain but instead reflects interconnected structural deficiencies across the broader WEF nexus system.

Energy insecurity in Fig. 10(b) emerged as one of the most critical dimensions of vulnerability because of its extremely low adaptive capacity relative to exposure and sensitivity conditions. The sector recorded an exposure score of 0.463, sensitivity of 0.424, and the lowest adaptive capacity of 0.392 among all sectors. The heavy reliance on a single biomass of firewood where long distances are covered to obtain it explains the fuel scarcity, physical accessibility constraints, and widespread use of traditional 3-stone cookstoves in the settlement. A consistent observation was noted in qualitative findings where firewood reliance (94.6–100%) led into use of 3-stone and lorena cookstoves with long distances covered to acquire the fuel. In Kalobeyei refugee settlement based in northwestern Kenya, 95% of households have been reported to exchange and sell their food to buy the inadequate firewood, a main cooking fuel for them [90]. However, the 3-stone stove shown in Fig. 11(a) has been reported to be associated with low combustion efficiency and elevated indoor air pollution exposure, often exceeding recommended health thresholds [91–93]. Bidibidi's energy insecurity therefore, extends beyond fuel access limitations to include important health and environmental dimensions. Adaptive capacity was low since access to alternative modern clean cooking technologies like solar cookstoves and briquettes was extremely limited. This does not come as a surprise due to the rural nature of Bidibidi. Majority of FGDs, KIIs, and IDIs reported to have just seen somewhere but not actually use the solar cooker in Fig. 11(b), and briquettes in Fig. 4(c). The market systems in rural-based refugee camps are still under developed let alone experiencing unreliable power supply and high costly insufficient energy infrastructure [87,94]. Nevertheless, the willingness to adopt instalment-based payment systems for energy technologies and collective social structures evidenced by community group participation suggests the presence of unmet demand for affordable clean energy financing mechanisms that can partially moderate household level energy vulnerability even where technological access is constrained. Njenga et al. [90]., noted refugee community women groups' success in briquette making as long as market and raw materials sourcing challenges are addressed through possible exploration of briquette kiosks, using invasive biomass species like Prosopis juliflora, and initiative integration in development plans.

Food insecurity recorded the lowest Vi among the three sectors, although the sector exhibited the strongest imbalance between sensitivity and the other ESAc dimensions as shown in Fig. 10(c). The Food sector registered ESAc scores of 0.392, 0.608, and 0.528, respectively. The elevated sensitivity score indicates that just even a slight disruption in food access and production, it can generate disproportionately severe

Fig. 11. Cook stoves used: (a) 3-Stone stove; (b) Solar electric cooker; (c) Single spot lorena stove; (d) 2 Spot lorena stove.

welfare impacts at household level. This reflects the weakness of subsistence farming i.e., limited productivity, poverty, and agricultural resources scarcity seen within Bidibidi and other camps like Nakivale, Rhino and Kyangwali [95–97]. 30,000 UGX was the most possible income an average farmer would generate per month according to this study's qualitative insights. Table 3 shows that low meal frequency and food losses from pest attacks were the dominant sensitivity drivers within the food system. These findings demonstrate that food insecurity in Bidibidi is shaped simultaneously by inadequate dietary access and unstable agricultural productivity. Beans emerged as the dominant household protein source, which carries important nexus implications because its preparation required prolonged cooking durations and therefore increasing household cooking fuel demand. FGDs, KIIs, and IDIs also presented beans as the most difficult sauce to cook due to its high fuel consumption, forcing people to often substitute it with green vegetables. The interactions revealed that about 5 to 20 medium pieces of firewood are used to cook a normal meal per day in the settlement. Hafner et al. [98], found a 3-stone stove to take a range of 145 to 200 min in cooking a beans meal and about 74 to 81 min for vegetables. Prior soaking of the beans has proved reduction in the cooking time [99,100]. The close interdependence between food and energy insecurity within refugee livelihoods of Bidibidi can therefore not be neglected in seeking solutions to the challenges faced by settlement's food and energy systems. The relatively higher adaptive capacity observed in the food sector was largely associated with community group participation and partial access to small-scale solar-powered irrigation systems as shown in Table 3. However, income diversification remained extremely limited, indicating continued dependence on humanitarian assistance and subsistence agriculture. Similar constraints have been widely documented in other refugee settlements where restricted livelihood opportunities, weak local economic and resources integration limit household resilience and adaptive potential [101]. Wu et al [102]., stressed for the importance of livelihood resilience for a household in order to reduce stress on natural resources dependence.

Water insecurity recorded the highest overall vulnerability score (see Table 6) and displayed the most balanced ESAc structure, with all the scores converging around 0.50 as shown in Fig. 10(a). Rather than indicating resilience, this nearly symmetrical distribution suggests an inadequate equilibrium in which weaknesses across all three dimensions support one another. Any deterioration in water infrastructure access, service delivery, and adaptive resources can therefore rapidly intensify overall vulnerability from water insecurity. The exposure profile of the water sector was primarily driven by limited proximity to reliable water sources rather than by direct climatic stressors as shown in Table 3. Distant water access points leading to time wastage was similarly a major issue mentioned in the FGDs, KIIs, and IDIs. Droughts was another climate-sensitive issue noted due to the dry-up of water streams, an alternative water source in the dry season. A dried-up water stream and lined-up jerrycans waiting for water to be made available via a tap stand point by OPM is shown in Fig. 12. The settlement is in a locality of West Nile with annual average rainfall of 1300 mm and temperature of 30 °C. The months of January to April recorded highest temperatures of 36 °C [40,103,104]. This makes rainwater harvesting a challenge adding on to the significant absence of iron sheet roofs and gutters [69]. These findings suggest that water insecurity in Bidibidi is more strongly associated with infrastructure and service accessibility deficits than with absolute water scarcity conditions. A water supply assessment study relatedly revealed that despite a person in Bidibidi needing on average 18 litres/day, 50% had <15 litres/day and 40% were living > 500 m away from water source [49]. Carmen et al. [105], highlighted the need

Fig. 12. (a) Dry-up of water stream; (b) Lined-up jerrycans in zone 4 waiting for water to be made available via a tap stand point.

of setting up more additional water points with secure lighting at night to ease on the water scarcity and off-site water infrastructure access which exacerbated the risk of sexual gender-based violence on adolescent and young girls in Bidibidi. Interestingly, solar pump repair skills existed in the settlement, indicating that technical maintenance capacity has partially developed along with infrastructure deployment.

The ESAc analysis demonstrates that vulnerability within Bidibidi is fundamentally cross-sectoral. Water, energy, and food insecurities interact through mutually supporting infrastructure deficits, environmental pressures, and constrained adaptive resources. The closeness of Vi scores across all sectors further confirms that sustainable intervention strategies in refugee settlements require integrated WEF nexus approaches especially bottom-up rather than isolated top-down sector specific responses.

3.3. Implications on policy and technology design

The integrated AHP and ESAc analysis findings in this study provide a strong empirical basis for designing integrated WEF nexus policies and technologies for Bidibidi refugee settlement. While the AHP analysis identified the most critical sustainability deficits across water, energy, and food systems, the ESAc framework further explained the structural conditions driving vulnerability through exposure, sensitivity, and adaptive capacity dynamics. Together, the two analyses demonstrate that WEF insecurities in Bidibidi are interconnected and cannot be effectively addressed through isolated sectoral interventions. More importantly, the study demonstrates why the bottom-up approach (see Fig. 13) is more suitable than conventional top-down humanitarian planning in refugee settlements. Existing refugee interventions in

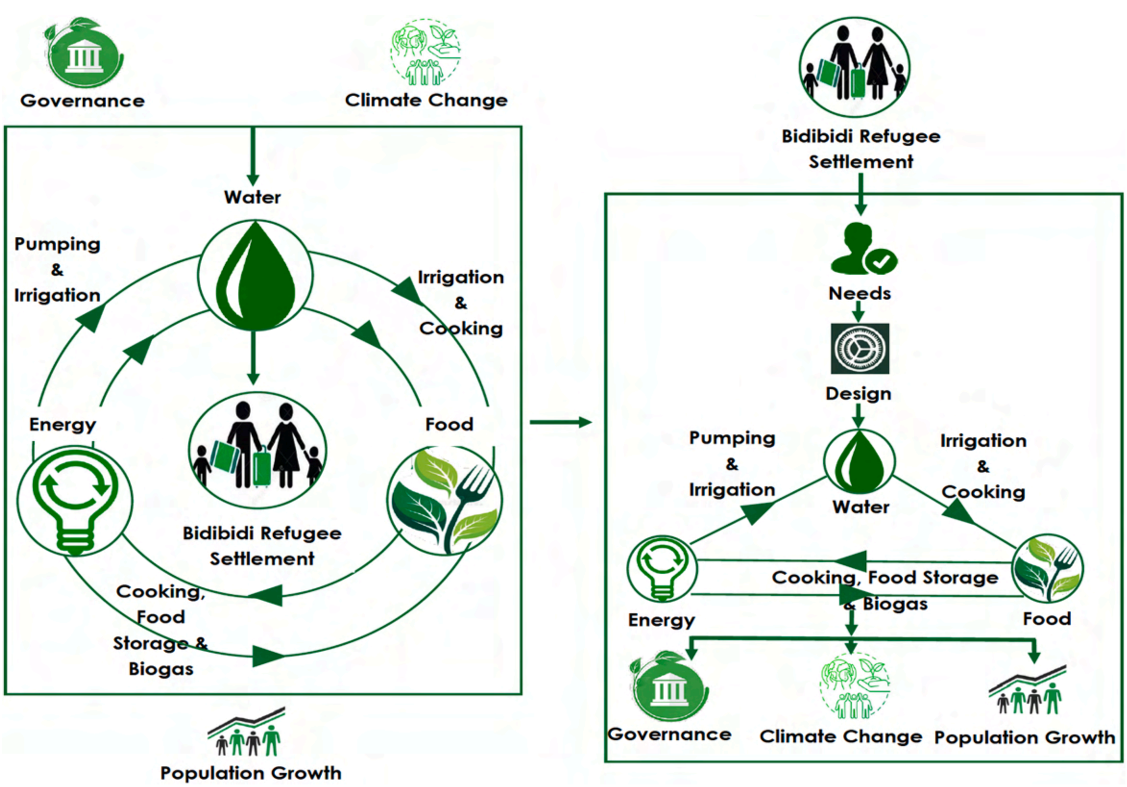

Fig. 13. Transformation from current to a proposed WEF nexus approach for Bidibidi refugee settlement.

Uganda are largely guided through centralized humanitarian frameworks such as the Comprehensive Refugee Response Framework (CRRF), the Sustainable Energy Response Plan (SERP) for Refugees and Host Communities, and broader humanitarian support systems coordinated through United Nations High Commissioner for Refugees (UNHCR) and the Office of the Prime Minister (OPM) [106]. Although these frameworks have improved baseline access to water, food assistance, and energy services, studies show that many interventions remain generalized and insufficiently adapted to the local nexus realities of refugee settlements like Bidibidi. The current Uganda's refugee protection model of self-reliance and economic inclusion has been labelled risky for uptake by the international community and other African refugee hosting countries due to its major failure in empirically understanding resource distribution through voices and perspectives of refugees at local level to guide policy [101]. Challenges recorded by the model and its approach include; placement of camps in remote and underdeveloped areas, limited ability of local economies to support refugees, and inadequacy of natural resources like land [107,108]. In contrast, the bottom-up mixed methods approach used in this study captured locally experienced resource interlinkages, resource insecurity vulnerabilities, existing coping systems, and how they guide formation of practically feasible solutions for Bidibidi refugee settlement. The findings therefore provide a more context-responsive basis for designing interventions aligned with existing community capacities and livelihood systems rather than externally imposed assumptions.

The strongest nexus deficit of Bidibidi emerged within the water–food system where agricultural production is highly exposed to seasonal rainfall variability and dry-season food stress. The current humanitarian water principles in refugee settlements remain heavily focused on domestic water supply, sanitation and hygiene while productive agricultural water access receives limited attention [73,109–111]. This policy imbalance directly contributes to continued food insecurity and encourages dependence on humanitarian food assistance [96]. A shift toward integrated water–food planning in refugee settlements is necessary. The most effective direction is the expansion of borehole-based solar-powered pumping water systems to supply smallholder irrigation and domestic use. With ground water availability already reported despite majority of the settlement being in a low potential access area [49], policy backed solutions can include; conducting detailed groundwater mapping in Bidibidi to identify the best water rich locations and maximumly exploit their potential; exploring blend of small-scale drip irrigation with hydroponics and pot farming. Solar powered water pumping systems were recorded to be a success for refugee camps in the East and Horn of Africa [112]. Potential has also been noted in container gardening easing food insecurity for arid and semi-arid regions e.g., vegetables like Hibiscus sabdariffa and cabbages were successfully grown in dry parts of northern Ghana [113,114]. Solar pump repair skills and other local capacity building can be further strengthened through establishment of accredited vocational training schools within the settlement hence ensuring long-term sustainability and reduced dependence on externally managed technologies.

The food sector findings further highlight the importance of post-harvest management technologies. It was realized that food insecurity in Bidibidi is not solely a production problem but also a storage and value-retention challenge. Existing refugee food policies and humanitarian programmes primarily emphasize food distribution and production support, while post-harvest preservation receives limited operational attention. An unclear collaboration was noticed between United Nations (UN) agencies where Food and Agricultural Organization (FAO) focused on urban agriculture, while World Food Programme (WFP) implemented cash and voucher interventions [115,116]. This study's findings present low-cost air tight storage technologies such as Purdue Improved Crop Storage (PICS) bags, mini evaporative coolers, and communal solar cold storage on a Pay-As-You-Go (PAYGO) model for farmer groups as the most practical interventions capable of reducing post-harvest losses while improving household food stability in the settlement. Such interventions are particularly relevant in refugee settlements where upfront technology costs remain prohibitive. PICS bags have been shown to reduce insect pests by up to 99%, prevent mold growth, and safely preserve grains for >5 months, while evaporative cooling can lower temperatures by up to 10 °C and extend vegetable shelf life by about 4 days. Although PAYGO systems have enabled some low-income households to access LPG, their effectiveness has been seen to be limited by low pay margins of users [117–119]. Policies under WFP and OPM food security programming should therefore expand beyond food access indicators to include post-harvest loss reduction and decentralized preservation support as formal refugee resilience targets.

The energy sector presented a more complex nexus trade-off where extreme firewood dependence and widespread use of inefficient three-stone stoves masked the significant environmental and health vulnerabilities. Expanding fuelwood collection contributes to deforestation, land degradation, and pressure on the same ecological systems that support food production [40,41,78]. This demonstrates that Uganda's SERP framework has not yet significantly transitioned refugee households toward clean cooking systems. This study's findings support the need for integrated clean cooking policies that simultaneously address energy access, environmental sustainability, and livelihood resilience. Integrating livestock-powered biogas system in schools, exploiting high density briquettes with efficient stoves and pressure cookers, alongside massive planting of fast-growing, locally adapted trees emerge as the most context-appropriate sustainable energy solutions for Bidibidi. Refugee community women groups' briquette making has been observed to be successful as long as market and raw materials sourcing challenges are addressed through possible exploration of briquette kiosks, using invasive biomass species like Prosopis juliflora, Eucalyptus grandis, Senna siamea, Calliandra calothyrsus and initiative integration in development plans [88,90]. Briquette compatible efficient cookstoves provide an immediate pathway for reducing firewood demand without requiring major behavioural transitions, while briquette production offers opportunities for community group-based enterprise development using branches of already planted tree species and locally available agricultural residues after harvest.

Across all sectors, the findings consistently demonstrate that existing community structures constitute the most important adaptive capacity asset within the settlement. Community energy groups, farmer associations, and local support networks already perform informal coordination, knowledge sharing, and resilience. As a result, future WEF interventions should be institutionally routed through these local structures rather than relying exclusively on externally designed top-down delivery systems. The bottom-up mixed methods approach used in this study was therefore critical because it captured locally grounded priorities, vulnerabilities, and adaptive practices that may be overlooked in centralized planning frameworks. Ultimately, the results suggest that WEF nexus policies in refugee settlements are likely to be more effective when solutions are co-designed with communities, aligned with existing local capacities, and implemented through participatory governance mechanisms rather than through externally imposed sector-specific interventions.

4. Conclusion

This study demonstrated that water, energy, and food resource insecurities in Bidibidi refugee settlement are highly interconnected and cannot be effectively addressed through isolated sector-specific interventions. By integrating the AHP with the IPCC's ESAc framework within a bottom-up mixed-methods approach, the study moved beyond descriptive WEF nexus assessment toward a more empirical understanding of sustainability performance and vulnerability dynamics in a refugee setting. The integrated WEF nexus index classified Bidibidi as marginally sustainable, while ESAc analysis revealed intermediate vulnerability across all WEF sectors, confirming that resource insecurity operates as a joined system shaped by infrastructure deficits, environmental stress, and limited adaptive capacity.

The findings identified critical nexus deficits within the water-food and energy-food systems. Extremely low irrigation accessibility constrained food production and encouraged dependence on rainfall-based agriculture, while heavy reliance on biomass energy intensified environmental degradation and health risks despite supporting household energy access. In addition, weak post-harvest preservation systems limited food retention and livelihood resilience. These results highlight the importance of integrated interventions capable of generating simultaneous benefits across multiple resource sectors.

The study further demonstrated the practical value of a bottom-up approach in refugee settlements like Bidibidi by capturing locally experienced resource interactions, coping mechanisms, and community priorities often overlooked in centralized humanitarian planning. Policy and practice should therefore prioritize decentralized solar-powered irrigation, affordable clean cooking systems, community-based briquette enterprises, post-harvest preservation technologies, and participatory governance mechanisms aligned with local capacities. Future research should incorporate longitudinal assessments, seasonal variability, and climate projections using a larger sample size to further strengthen WEF nexus planning and resilience in displacement contexts.

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CRediT authorship contribution statement

Michael Lubwama: Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ibrahim Kikomeko:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Vianney Andrew Yiga:** Writing – review & editing, Methodology, Investigation, Formal analysis.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Michael Lubwama reports financial support was provided by European Climate Infrastructure and Environment Executive Agency. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Date will be made available upon reasonable request to the corresponding author.

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