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# Insights on Water and Climate Change in the Greater Horn of Africa: Connecting Virtual Water and Water-Energy-Food-Biodiversity-Health Nexus

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**Abstract:** Water is the key limiting factor in socioeconomic and ecological development, but it is adversely affected by climate change. The novel virtual water (VW) concept and water, energy, food, biodiversity, and human health (WEFBH) nexus approach are powerful tools to assess the sustainability of a region through the lens of climate change. Climate change-related challenges and water are complex and intertwined. This paper analyzed the significant WEFBH sectors using the multicriteria decision-making (MCDM) and analytic hierarchy process (AHP) model. The AHP model demonstrated quantitative relationships among WEFBH nexus sustainability indicators in the Greater Horn of Africa countries. Besides, the net VW imports and water footprints of major staple crops were assessed. The composite WEFBH nexus indices varied from 0.10 to 0.14. The water footprint of crops is increasing period by period. The results also revealed that most countries in the study area are facing WEFBH domains unsustainability due to weak planning or improper management strategies. The strong policy constancy among the WEFBH sector is vital for dissociating the high-water consumption from crop production, energy, environmental, and human health system. Thus, this study enhances insights into the interdependencies, interconnectedness, and interactions of sectors thereby strengthening the coordination, complementarities, and synergies among them. To attain sustainable development, we urgently call all public and private entities to value the amount of VW used in their daily activities and design better policies on the complex WEFBH nexus and future climate change.

**Keywords:** analytic hierarchy process; biodiversity; climate change; Greater Horn of Africa; nexus analysis; sustainable development; virtual water

## 1. Introduction

Water stands as a common denominator that links nearly every sustainable development goal (SDG) of the United Nations [1]. In the light of the climate crisis, the issue of global virtual water (VW) transfers in the water, energy, food, biodiversity, and human health (WEFBH) nexus is under-studied [2]. The nexus of WEFBH is shaped by the manifold complex and mutual interlinkages between water consumption, energy production, food systems, environmental and public health [3]. The water, energy, food, biodiversity, and human health sectors support and fulfill many of humanity's demands for goods and services [4]. There are widespread insights, especially in the literature on the water–energy–food (WEF) nexus for different sectors, spatial and temporal dimensions by coupling one domain to another [5–12]. Currently, biodiversity and human health approaches were not presumably thoroughly taken into account in this regard [13–15]. Conventionally, questions toward sustainable environmental management are frequently discussed with multisectoral policy approaches (or siloes) [16]. However, there is still complexity in the patterns between WEF nexus and decision-making entities [17–19]. The integration of biodiversity and human health factors into the current WEF system/nexus can facilitate handling the trade-offs and synergies between resources [20]. Accordingly, to grow crops, maintain cattle, and produce food requires water, productive land, energy, healthy ecological, and human capital [21]. Furthermore, rather than cross-sectoral crises affecting areas such as agriculture, energy, manufacturing, cities, ecosystems, and general wellbeing, the importance of water in reducing climate risks is overly emphasized [22]. To ensure sustainable production and productivity, therefore, the WEFBH nexus approach is expected to preserve and secure the socioecological system [23]. However, the nexus within water should include the assessment of interdependencies between biodiversity, human health, and climate change, crucial for human well-being [4,24]. An innovative manner to address this intricacy is the 'nexus approach', 'nexus thinking', and 'nexus planning', which is an auspicious way to detect co-benefits, synergies, and trade-offs between sectors [5,25]. Such ways foster knowledge-based policies and specialized practice toward sustainability and resource productivity which pertain to constraints allied to water and food-based resources availability, socioeconomic growth, and controlling changes in climate through forms [26,27].

Recently, the World Water Development Report 2020 proposed many adaptations and mitigations for the water–climate–energy–food–environment nexus [22] and models: coupling multiple nexus factors water–climate [28], water–food [29], water–energy [30,31] were developed to link up with the impacts of climate variability and the water, human health, environment, and nutrition nexus [13,15,22]. However, the inherent complexities and uncertainties are still hindering the understanding of WEFBH and the complex relationship between water resources, VW, and other sectors. The VW notion, biodiversity, and human health are crisscross issues and were ignored in the currently existing famous WEF nexus approach. Therefore, incorporating VW, biodiversity, and health domains in the nexus assessment as discrete segments aid in gaining a deeper intuition of the influential contribution of the considered sectors on food, water, and energy security.

A specification of WEF security-related sustainability metrics and a collection of concrete criteria that weight resources management on a particular spatiotemporal scale, proved to be was the first step in achieving an integrated assessment of WEF sectors [32,33]. The [15,34] use of multicriteria decision-making (MCDM) method to structure mathematical relationships between discrete and interlinking water, human health, environment, and nutrition sectors for better and easy understanding and interpretation has been studied. Consequently, Momblanch, et al. [35] employed scheme modeling techniques to investigate the effects of change impacts on the food–energy–water–environment linkages in the mid-21st century. The multisectoral nexus approach (MSNA) used in this research study refers to "organized scientific research and design of effective policy priorities and tools that concentrate on synergies, trade-offs, and co-benefits evolving in the interactions between land, water, energy, food, environment, and climate at environmental, socioeconomic, and governance levels" [13,36]. However, the contribution of biodiversity in this nexus is not appearing in the project. Meanwhile, to fight against climate change, the paradox of affecting biodiversity emerges [37]. The MSNA's uniqueness lies in its ability to provide prospects for comprehensive policy alignment and nexus-related impacts of implemented policies, highlighting highly relevant reaction mechanisms and relations. This attitude emerged from other multi-intersectoral frameworks, such as ecology-related-services analysis, in that it establishes a framework for integrative information generation and cross-sectoral management by ensuring adequate consideration to all sectors concerned [36,38].

De facto, the concept of "VW Trade" proposes a trade-based solution to the global water crisis while enhancing the water resource management from basin to regional levels [39]. An Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) declared that cross-sectoral collaboration, planning, and enforcement support the achievement of both global environmental and societal goals [4], but the nexus approach does not only evaluate natural resource constraints from a holistic perspective but also determines how strategic policy can indeed be reformulated to resolve the most consistent challenges and efficiently deliver possible feedback and oriented mitigation at critical matters to applied scales. The WEFBH nexus analysis requires holistic approaches that inextricably consider all anthropogenic interventions and interactions with the environment.

The Greater Horn of Africa (shortened as 'GHA') is the most WEFBH-based worldwide challenged area [40,41] and currently faces consequences related to the current triple menace including overpopulation, combined effects of climate change, and the COVID-19 pandemic which increased the rate of water scarcity and food insecurity/food poverty [42]. Most African countries have annual population growth rates above 3% per year [43]. According to World Health Organization (WHO), the GHA will have a population of 545 million people in 2050 (i.e., over 20% of the projected total population of Africa) [44]. The GHA established water, energy, food, biodiversity, and human health policies. Moreover, some studies explored WEF nexus via single study areas, for example, Rwanda and Ethiopia [45], Uganda and Tanzania [46], and Kenya [47], but cross-sectoral interlinkages between WEFBH nexus, their impacts, and consequences are largely unknown and under-researched. The GHA is a promising area that can facilitate us to understand the WEFBH nexus because of the aforementioned issues.

Therefore, this study aimed to build a detailed conceptual framework and examine the WEFBH nexus from the perspective of the VW concept and climate change to gain insight into interactions between all relevant sectors and ensure continuous development of adaptation or/and mitigation measures toward sustainable water resource management and human health. This paper can be also used to help policymakers gather more information about effective interventions through the nexus approach and integrating VW towards socioecological systems, as well as assisting in steering regional policy debates in very normative and restrictive ways.

After the introduction and literature review, we describe the study area and discuss the climatic scenarios under water stress, and the general conceptual framework of the WEFBH nexus. Then, the methodology, statistical calculation, and data are used to estimate the VW trade of staple crops, nexus analysis, and the relationship between VW and WEFBH sector (Section 2). Section 3 interprets the relevant findings. We discuss the results and policy implications, future developments, and the limitations of the study (Section 4), with the conclusion (Section 5).

## 2. Material and Methods

### 2.1. Study Area

This study focuses on the GHA region, surrounded by two large bodies of water (i.e., the Red Sea and the Indian Ocean), comprising eleven countries, which include Burundi, Djibouti, Eritrea, Ethiopia, Kenya, Rwanda, Somalia, South Sudan, Sudan, Tanzania, Uganda (Figure 1).

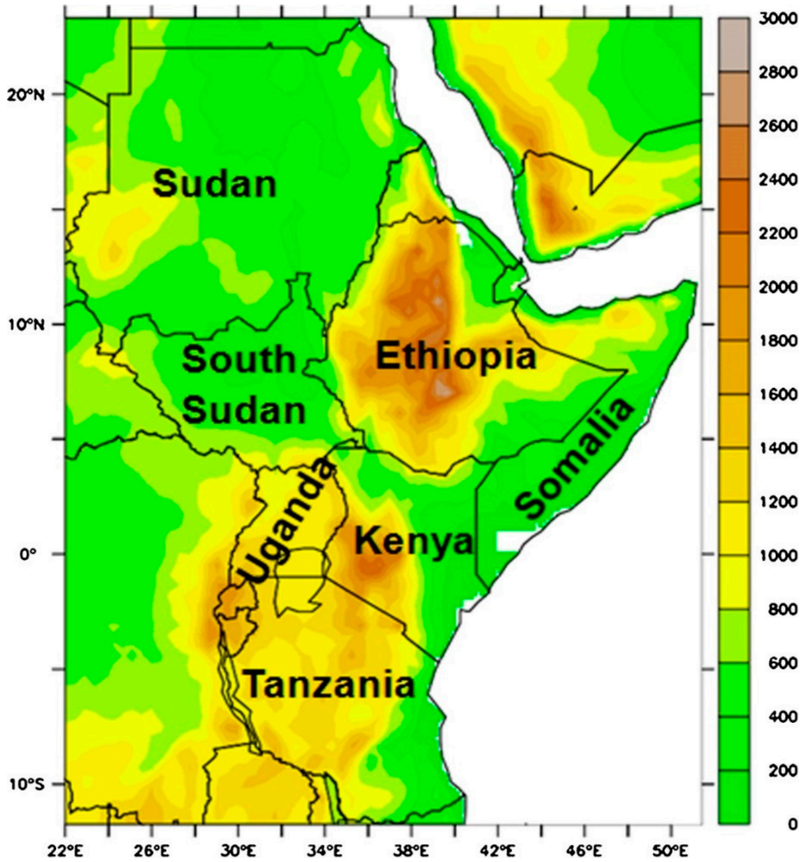


**Figure 1.** The GHA region. The numbers on the bar express the topography in meters above sea level (asl). The Global Multiresolution Terrain Elevation Data 2010 (GMTED2010) was extracted from the Center for Earth Resources Observation and Sciences (EROS) of the U.S. Geological Survey [48].

The GHA is highly affected by complex bearings of topography, lakes, seasonal dynamics of tropical circulation, and maritime oscillations [49]. The strong seasonal and inter-annual variability of the climate system is one of the key drivers of severe events in GHA (e.g., droughts and storms). The El-Nino-Southern Oscillation (ENSO), sea surface temperatures (SSTs), and land-atmosphere associated feedbacks, for example, are all linked to the manifestation of drought in East Africa due to their uncertainty and variability [50,51]. Thus, the GHA has average annual precipitation between 800 and 1200 mm with higher rainfall in the uplands and lower rainfall in southern Somalia and northeastern Kenya [52]. Obviously, the GHA's climate encompasses three main rainy seasons annually ranging from March to November [53]. The water resources are unevenly distributed. The hydrological regime is highly seasonal due to climatic diversity and variability. The spatial patterns of rainfall and actual evaporation (ETa) show that upstream watersheds (i.e., Uganda, southern Sudan, and southern Ethiopia) have high values, whereas downstream watersheds (i.e., Djibouti, Somalia, and Eritrea) have low values [54]. Currently, on average, $82 \times 10^9$ $m^3$ of water is withdrawn from GHA region waters every year for irrigation [55,56].

Figure 2 shows the amount of water consumed by the main sectors including agriculture, industry, irrigation, municipal, and energy [57]. Based on the annual average basis, Sudan consumes the highest amount of water used for agriculture in the GHA ($25.91 \times 10^9$ $m^3$) followed by Ethiopia which requires ~$89.3 \times 10^9$ $m^3$ the amount of water for environmental flow (EF) requirements. Therefore, the EF represents the amount of and timing of freshwater flows and levels necessary to sustain aquatic ecosystems which in turn, foster sustainable livelihoods, human cultures, economies, and wellbeing [58].

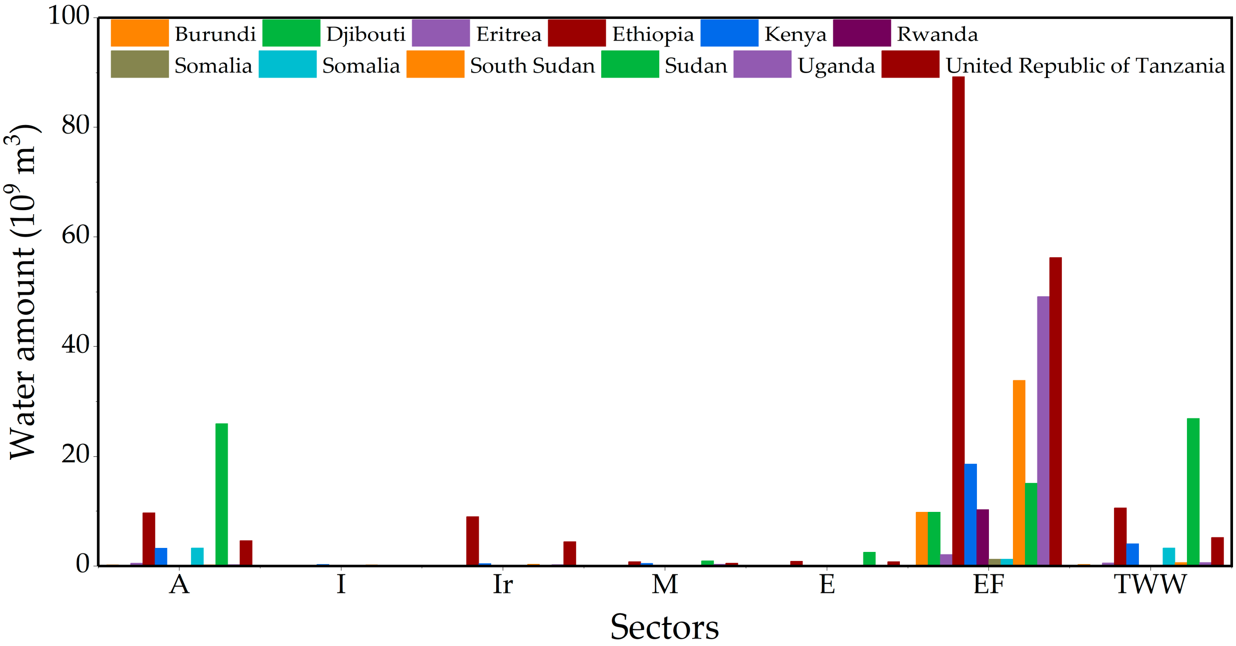


**Figure 2.** Annual average of water withdrawn in GHA region by different sectors during 2010–2019 including agriculture (A), industry (I), irrigation (Ir), municipal (M), and water loss in energy production (E) with as environmental flow requirement (EF) and the total water withdrawal (TWW).

## *2.2. Socioeconomic Features*

Although regional economic growth is rising, there is a significant gap in growth within the subregion. The population is relatively fast-growing with over 289 × $10^6$ people in 2020 and projected at 533 × $10^6$ people in 2050 [59]. To feed its rapidly growing population, the area is overly dependent on rainfed agriculture [60,61]. Moreover, Agricultural productivity, which is already poor by global standards, will continue to decline for some staple crops. For example, between 2000 and 2050, South Sudan experienced and is expected to experience a yield loss of 5–25% [62]. Though, the GHA is classified as a food-insecure region resulting in climate change, due to drastic rising temperatures, sea level, political instability and fragility, state-driven conflict, corruption, and poor governance [63,64]. Moreover, the above-mentioned structural challenges are coupled and interacting with one another [65]. In addition, the GHA states are endowed with considerable energy resources which include hydroelectric power, natural gas, petroleum, geothermal energy, coal, tourbillon, biomass, solar, and wind energy. The Nile Basin produces more than 20 GW [66].

## *2.3. Climate Scenarios*

Climate change threatened the GHA's water resources. Several reports show that rainfall in the southern part of Africa has recently declined, most likely as a consequence of climate change [67–69]. Various non-climate-related drivers of water scarcity and pollution such as fragility, population growth, economic development, and confrontation seem to increasingly interact with such impacts [70]. In the coming decades, many parts of the GHA are projected to receive below-average rainfall, worsening food security and water availability in countries even suffering from drought. At the turn of the 21st century, in East Africa (EA), multiple studies predicted a high loss of 40% for maize production [71]. The study of Lobell and Field [72], based on EA climate data, confirmed that there would be a reduction in crop yield of primary crops (i.e., maize) of 16–20%, 24–31%, and 27–37%under B1, A1B, and A2 scenarios respectively. Mainly, water is required at various stages of food production. Rain-fed agriculture, which accounts for 69% of water withdrawals worldwide, is where the elevated temperatures and aridity will extremely impact remaining climate risks [22].

*2.4. General Framework for WEFBH Nexus*

The design of the WEFBH nexus structural framework was to summarize that water, energy, food, biodiversity, and human health are all interconnected components of a healthy and functional socioecological system [15,73]. We referred to the intricate relationship between food, energy, water, biodiversity, and the human health field, and the components guide the dynamics of the socioecological system. The WEFBH nexus is the name given to this interconnected relationship (Figure 3). Therefore, we explored and clearly illustrated the hybrid framework named WEFBH nexus in the climate change lens, highlighting the foundational role of VW as the central aspect to WEFBH in reaching water, energy, food, and environmental security (Figure 4). The often-strong interlinkages across the WEFBH nexus could appeal to strengths and cross-benefits formerly also trigger tough decisions and trade-offs. Though, the assessments across sectors and boundaries are essential to maximizing overall proceeds [22].

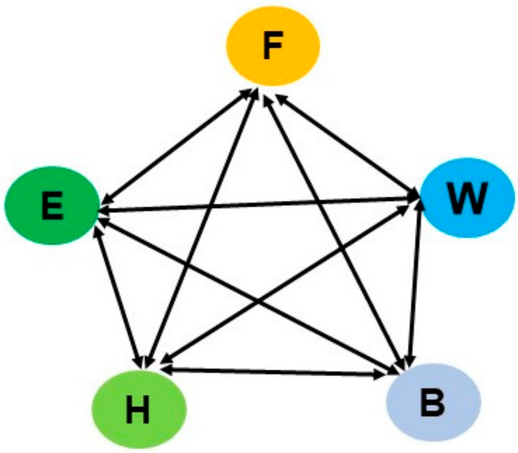


**Figure 3.** Simplified illustration of the complex interconnections between the nexus sectors. Turning clockwise direction, the capital letters represent Food (F), Water (W), Biodiversity (B), Health (H), and Energy (E) sector. The five sectors of the nexus, F, W, B, H, and E, are associated with one another thru various direct and indirect interlinkages. A direct interlinkage between two sectors is described as a change in one's status due to a change in the status of another, implying that the rest of the components do not interfere with the two first elements' special bond. Adapted from [13].

Sustainable food is concerned with producing sufficient food, fiber, or other plants or livestock production with sufficient nutritional values using environmentally friendly techniques (e.g., aquaponics, hydroponics, crop rotation, agroforestry, and among others), public health, human health communities, and animal welfare. It is a way of food production capacities that generates abundance while ensuring future generations' equity. Sustainable water strives to provide efficient or/and sufficient water to meet multiple needs of people as a resource. Despite the climate change effects, such as a shortage of rainfall and drought, or too much rain and flood resistance, water availability would remain constant. Sustainable energy deals with the generation of energy capable of being replenished in human life and thus does not cause long-term damage to the environment. Biodiversity underpins the ecosystem services provisioning, regulating, and functioning. Furthermore, it helps to mitigate and adapt to climate change while also promoting human wellbeing and creating jobs in different domains (e.g., agriculture, fisheries, forestry, and among others). A sustainable health system refers to a scheme that would change people's lives. It identifies ways to preserve or restore health while mitigating negative environmental impacts and maximizing opportunities to restore and enhance health for the profit of the current and future generations' health and well-being.

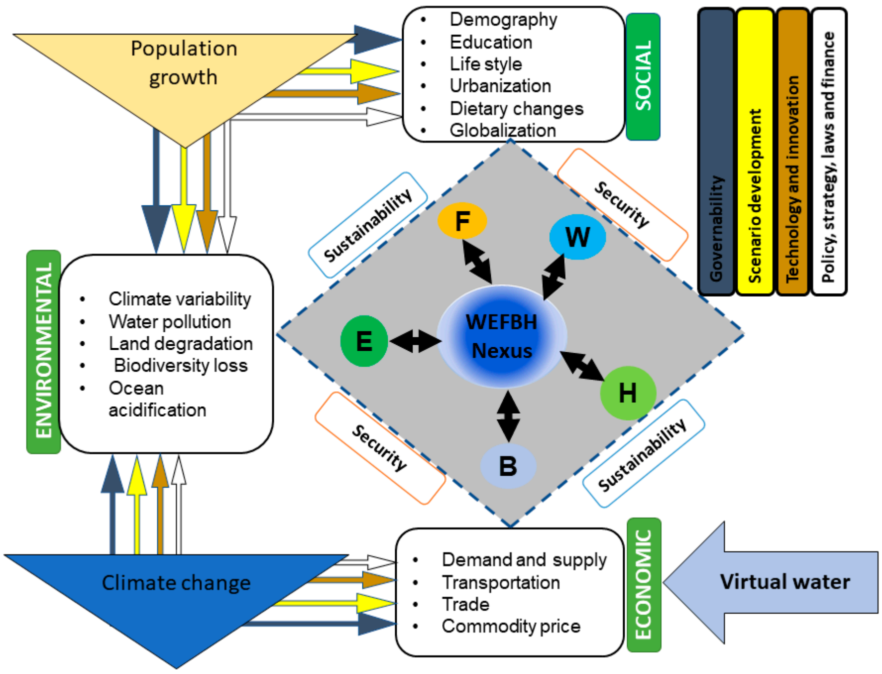


**Figure 4.** The WEFBH nexus and key positions of VW. Nexus management refers to governability, scenario development, technology and innovation, policy strategy, laws, and finance. Sustainability and security stand for the balance between trade-offs and synergies among each of the five sectors (i.e., water, food, energy, biodiversity, and human health). The VW is common binding material for all interactions within securities, while climate change and population growth are the foremost driving factors in the WEFBH nexus.

This predominant merging of WEFBH nexus, conceptually, adding population growth, climate change (as driving forces), and the environment itself, as cross-cutting issues to the frequently known WEF nexus. VW serves as the mutual bonding element to the whole system at all scales and in every step of production. Decisions taken in one field can raise risks and have negative consequences in another, but they can also have positive consequences. Furthermore, the interlinkages and trade-offs among these capitals challenge the attainment of water, energy, food, human health, and environmental points at the same time [8]. The climate, water, energy, food, biodiversity, and health are all intrinsically tied and mutually beneficial. These resources are essential input into socioeconomic development and population growth relies on an unswerving supply of water, energy, and food. Humans benefit from their ecosystem services [74].

### 2.5. Selection of Sustainability Indicators That Link VW Concept and WEFBH Nexus

Indicators are critical tools for comprehending, interacting, and assessing environmental strategies and practices [75]. The indicators that were chosen effectively decide the "lens" through which one sees the program and are thus crucial in shaping human judgments and decisions [75,76]. If the metrics for sustainable development have been established, they must be "quantified" in a broad context using both quantitative and qualitative methodology [77]. Despite their critical importance for policy and planning, most indicator sets for sustainable development have indicators for each of the pillars but ignore the ties between them [78]. However, The WEFBH nexus's central goal is to ensure resource protection through long-term, cross-sectoral resources planning [32]. Using an integrated approach, evaluating the synergies and trade-offs between diverse sectors to optimize resource efficiency was achieved by first identifying the interconnection between sectors such as WEF security, plus sustainability indicators, using differentiated methods at various temporal and spatial scales [5,33,79,80] while adapting optimum policies and institutional arrangements [21]. Water, energy, food, ecological, and human health security are important drivers of resource sustainability [81,82], as defined in Table 1. The indicators that do not explicitly represent the WEFBH nexus were left off the list. We considered the three pillars of sustainability characterized as follows ecological, social, and economic sustainability [83].

**Table 1.** The SDGs indicators are used to create the relationship between the WEFBH nexus.

| Nexus Element | Sub-Element | Items | Units | Indicator |
|---|---|---|---|---|
| W | Water security | Fraction of population having access to healthy drinking water | % | 6.1.1 |
| | | Fraction of bodies of water with good tolerable water quality | % | 6.3.2 |
| | | Level of water stress | % | 6.4.2 |
| E | Energy security | Fraction of population with access to electricity | % | 7.1.1 |
| | | Fraction of population with primary reliance on clean fuels and technology | % | 7.1.2 |
| | | Energy related-$CO_2$ emissions | $tCO_2$/capita | 9.4.1 |
| F | Food security | Prevalence of undernourishment | % | 2.1.1 |
| | | Cereal yield | t/ha | 2.4.1 |
| B | Ecological security | Average area that is protected in terrestrial sites important to biodiversity | % | 15.3.1 |
| | | Forest area as a fraction of total land | % | 15.1.1 |
| H | WaSH (Water, Sanitation, and Hygiene) | Mortality rate due to unclean water and sanitation, and lack of hygiene | Per $10^5$ population | 3.9.2 |

Note: The metrics used in this study are similar to SDG indicators. They were selected from United Nations Statistics Division (UNSD) [84].

Moreover, the main inclusion criteria to define the VW and WEFBH nexus in the GHA region was the following: ① any indicators officially published by SDG Center for Africa and Sustainable Development Solutions Network [85] and United Nations [86], ② indicators that are closely attributed to the WEFBH nexus and its driving forces, or ③ any indicators that refer to water, energy, food, biodiversity, and human health sustainability. Consequently, the exclusion criteria were that any indicators that are not key to WEFBH securities were excluded. Although, not all indicators are considered.

*2.6. Nexus Analysis and Normalization of Indices*

The analysis of nexus necessitated the identification of all elements based on the existing problem and the precise research area [35]. We employed the multicriteria decision-making (MCDM) method, a tool for organizing and resolving complex decision-making and planning issues involving different criteria [87] (Figure 5). Furthermore, the Analytic Hierarchy Process (AHP), based on a hierarchical structure of different scales to judgments ratios [88], was integrated into the framework of the WEFBH nexus to assess the quantitative relationship between the various variables of a socioecological system [89,90]. The AHP uses a pairwise comparison matrix (PCM) to connect sustainability metrics (Table 2) whereas in this study, the PCM defines priority weights for each metric in comparison to the others in the form of indices.

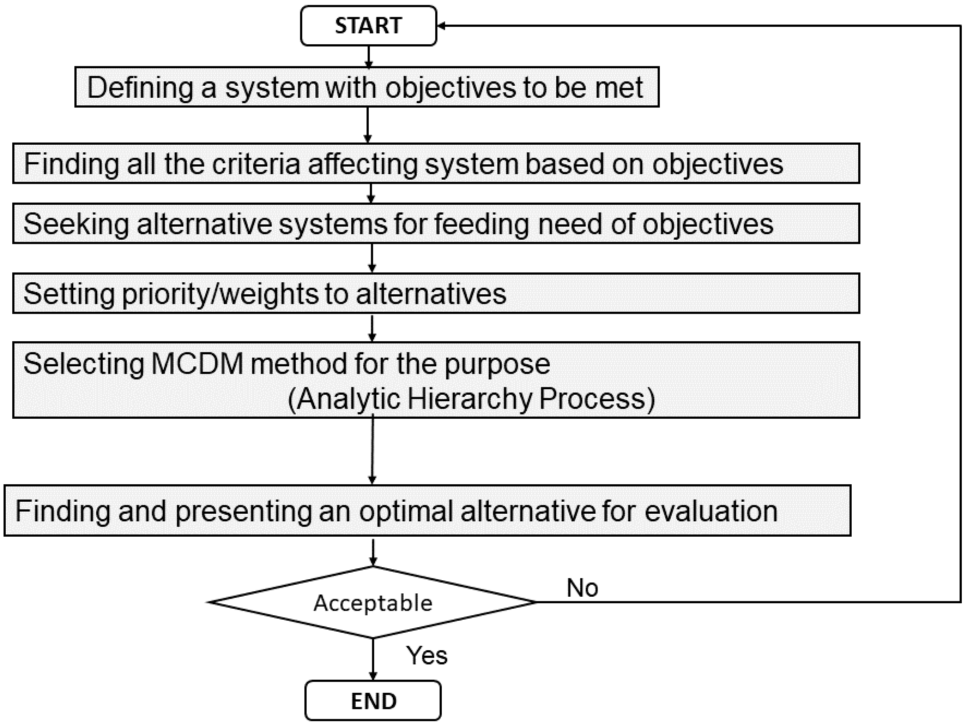


**Figure 5.** A common procedure for MCDM analysis. Adapted from [87].

**Table 2.** Situation of WEFBH nexus indicators in 2020.

| Sector | Sub-Sector | Indicator | BDI | DBT | ER | ETH | KEN | RWA | SOM | SSD | SDN | TZ | UG |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| W | Water accessibility | 6.1.1 | 60.8 | 75.6 | 51.9 | 41.1 | 58.9 | 57.7 | 52.4 | 40.7 | 60.3 | 56.7 | 49.1 |
| | Water quality | 6.3.2 | 45.8 | 63.6 | 11.9 | 7.3 | 29.1 | 66.6 | 38.3 | 11.3 | 36.6 | 29.9 | 18.5 |
| | Water stress | 6.4.2 | 10.5 | 7.9 | 11.2 | 33.3 | 33.2 | 1.4 | 24.5 | 4.2 | 118.7 | 13 | 5.8 |
| E | Access to electricity | 7.1.1 | 9.3 | 60.2 | 48.4 | 44.3 | 63.8 | 34.1 | 32.9 | 25.4 | 56.5 | 32.8 | 22 |
| | Clean fuels technology | 7.1.2 | 0.9 | 11.5 | 16.3 | 3.5 | 13.4 | 0.6 | 2.3 | 0.6 | 41.3 | 2.2 | 0.8 |
| | Energy related-$CO_2$ emissions | 9.4.1 | 0 | 0.6 | 0.2 | 0.1 | 0.3 | 0 | 0 | 0 | 0 | 0.2 | 0.1 |
| F | Food insecurity | 2.1.1 | 50.2 | 18.9 | - | 20.6 | 29.4 | 36.8 | 25.3 | 63.7 | 20.1 | 30.7 | 41 |
| | Crop production | 2.4.1 | 1.4 | 1.9 | 0.6 | 2.5 | 1.5 | 1.3 | 0.5 | 1.4 | 0.7 | 1.5 | 2.1 |
| B | Ecological security | 15.3.1 | 67.3 | 0.9 | 13.3 | 18.6 | 35.1 | 46.5 | 0 | 33.5 | 25 | 64 | 75.7 |
| | Forest management | 15.1.1 | 0.2 | 0 | 0 | 0.1 | 0.2 | 0.6 | 0 | 0 | 0 | 0.3 | 0.6 |
| H | WaSH related-diseases | 3.9.2 | 6.8 | 0.3 | 2.6 | 44.7 | 24.7 | 2.3 | 4.6 | 7.7 | 6.8 | 21.3 | 13.0 |

Legend: BDI: Burundi, DJI: Djibouti, ER: Eritrea, ET: Ethiopia, KEN: Kenya, RW: Rwanda, SOM: Somalia, SSD: South Sudan, SDN: Sudan, TZ: Tanzania, UG: Uganda. (-): No data. Data source: [85,86].

The AHP estimated the index for each indicator by the eigenvector of the matrix, and therefore, the results are normalized by dividing each score by the number of the components [91]. The matrix's priority weights of the matrix are defined by $w$ [89]. The total weight for each indicator was determined by the matrix's basic input, $S$, of $n$ criteria, with an order of $(n \times n)$ [92]. The $S$ is a pattern with elements $c_{ij}$.

$$S = \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1n} \\ c_{21} & c_{22} & \cdots & c_{2n} \\ \cdot & \cdot & \cdots & \cdot \\ \cdot & \cdot & \cdots & \cdot \\ \cdot & \cdot & \cdots & \cdot \\ c_{m1} & c_{m2} & \cdots & c_{mn} \end{bmatrix} = (c_{ij}) \in \mathbb{R}^{n \times n}$$

The reciprocal matrix is expressed as:

$$c_{ij} = \frac{1}{c_{ij}} \quad (1)$$

Thus, the matrix is normalized as pattern $T$, where $T$ characterizes the normalized pattern of $S$, and the elements are $t_{ij}$, and expressed as:

$$t_{ij} = \frac{c_{ij}}{\sum_{j=1} n\, c_{ij}} \quad (2)$$

The weight of each indicator ($w_i$) is settled as:

$$w_i = \frac{\sum_{j=1} n\, t_{ij}}{\sum_{j=1} n \sum_{j=1} n\, t_{ij}}\ i, j = 1, 2, 3 \ldots, n \quad (3)$$

The indices' weighted average is then used to construct the composite WEFBH nexus index. The indices are prominently linked to one another through a star graph that depicts the indicators' interconnectedness. The star graph graphically depicts the interconnectedness of various components [15].

However, the comparison matrix consistency was assessed via a consistency ratio ($CR$) inversely proportional to the consistency index ($CI$) (Equation (4)), to ensure the matrix consistent verification [93,94].

$$CI = \frac{\lambda_{max} - N}{(N-1)} \quad (4)$$

where $\lambda_{max}$ is the largest eigenvalue of an ($N \times N$), equal to the size of the pairwise comparison matrix. If a decision maker is perfectly consistent in specifying the entries, then $\lambda_{max} = N$ and $CI = 0$. If the decision maker is inconsistent, then $\lambda_{max} > N$ and the $CR$ were calculated using (Equation (5)) as proposed by [95]. The levels of consistency are calculated as follows:

$$CR = \frac{CI}{RI} \quad (5)$$

The $CR$ depends on the matrix size. The greater the size of the matrix, the more $CR > 0.1$ are acceptable. If the level of $CR$ is less than or equal to 10% or 0.1 (good) but the standard of 0.1 is merely the rule of thumb—the inconsistency is acceptable. If the threshold of $CR$ is greater than 10%, the subjective judgment is revised. However, it happens that individual $CRs$ are above 10%, therefore the consolidated matrix $CR$ is preferable [96].

### 2.7. Estimation of Crop Virtual Water and Water Footprint

The FAO's portal, WaPOR V2.0, for monitoring water productivity in Africa through open access to remotely sensed datasets [97], was mainly used to collect data for parameters and to calculate the $VW$ of and water footprint of the main staple crops in the GHA region including maize, rice, sorghum, wheat, millet, and barley. Therefore, the evapotranspiration of the reference crop ($ET_o$) data was directly collected from Water Productivity through Open access of Remotely sensed derived data (WaPOR) database from 2010 to 2019. Thus, the crop evapotranspiration ($ET_c$), equivalent to theoretical water demand, was also estimated by multiplying the $ET_o$ with crop coefficient ($K_c$).

The virtual water content ($VWC$) of a crop, on the other hand, refers to the ratio of the crop's water requirement ($ET_c$) to its yield per unit area of the crop (i.e., the amount of water required to produce per unit mass crop products). The following is the estimation formula:

$$VWC = 10 \times (ET_c / CY) \quad (6)$$

where $VWC$ denotes the crop's virtual water content ($m^3$/kg), $ET_c$ denotes the crop's water requirement during the growth cycle (mm), and $CY$ denotes the crop yield per unit area (kg/$m^2$).

Additionally, the regional water footprint of crop production ($WF$) can be determined using $VW$ consumption per unit crop yield and total crop yield. The equation is below:

$$WF = VWC \times CY\text{t} \quad (7)$$

where $WF$ represents the water footprint of the crop production ($m^3$), $VWC$ is the VW intake per crops' unit mass ($m^3/kg$), and $CY$t is the total crop yield in the region (kg). Based on the source and endpoint crop water use, the total water footprint of crops ($WF_{total}$) can be categorized into three groups: green water footprint ($WF_{green}$), blue water footprint ($WF_{blue}$), and grey water footprint ($WF_{grey}$) [98].

$$WF_{total} = WF_{green} + WF_{blue} + WF_{grey} \quad (8)$$

The $WF_{total}$ is estimated using the methodology established by [99]. The $WF_{green}$ denotes the amount of absorbed green water (i.e., rainwater), which is especially important in crop production. Then again, having a lower opportunity cost, the use of green water for the crop production commonly has fewer negative externalities than the use of blue water ($WF_{blue}$) (i.e., irrigation with water abstracted from ground or surface water systems). Despite this, green water volumes in exports have only been appraised infrequently [100]. The $WF_{grey}$ identifies the extent of freshwater contamination and is specified as the amount of freshwater needed to accumulate the pollutants' load based on current environmental water quality standards [101].

## 3. Results

### *3.1. Comparison of WEFBH Nexus Indices in the GHA Region*

The WEFBH composite indices were performed for eleven GHA countries based on the prior area of interest. The radar graphs were used to provide a clear visualization of interdependences, relationships, interconnections, and interactions within sectors; and sustainability resilience (i.e., sustainable or unsustainable). Therefore, the results revealed an unevenness in resource consumption and management. There is an evidence that most of the GHA countries focus on natural resources management (forest management), crop production (cereal yield improvement), the WaSH sector, and water quality (clean water accessibility). However, the main challenges for the WEFBH nexus in the GHA regions are water stress, energy accessibility, and food insecurity which considerably impact human health, for instance, in the case of Ethiopia, Djibouti, Eritrea, Somalia, South Soudan, and Rwanda (Figure 5). An achievement of ~63.0% has been done to promote forestry field development compared to energy accessibility, WaSH related diseases, and crop production. There is a need for improvement for the area of water accessibility and quality to fight against the WaSH-related diseases; energy sector (increasing the number of populations with access to electricity); water stress management (water use efficiency technologies); crop production (increasing the cereal yields) to combat food insecurity (Figure 6).

Certainly, the findings showed that Tanzania registered the allowable $CR$ (<0.03); this indicates that the likelihood and the normalized PWC matrix judgments were consistent. Contrarily, the $CR$ of the remaining countries ranged between 0.2 to 0.49. The results indicated that the comparisons are less consistent. Thus, the PWC is not consistent and needs to be re-evaluated, but it is acceptable. This is due to the size of the matrix. However, the overall composite WEFBH nexus index varies from 0.10 to 0.14 (Table 3).

**Table 3.** Estimation of the CR and composite WEBFH nexus indices in GHA.

| | BDI | DJI | ER | ETH | KEN | RWA | SOM | SSD | SDN | TZ | UG |
|---|---|---|---|---|---|---|---|---|---|---|---|
| C.R. | 0.4 | 0.34 | 0.34 | 0.33 | 0.49 | 0.49 | 0.39 | 0.2 | 0.24 | 0.03 | 0.25 |
| Composite WEFBH indexes | 0.14 | 0.13 | 0.13 | 0.12 | 0.10 | 0.11 | 0.11 | 0.12 | 0.11 | 0.10 | 0.12 |


**Figure 6.** Relationship between WEFBH nexus indicators in the GHA region in 2020. Each single radar graph shows the performance of sustainable indicators. Indicators presented in Table 2 were normalized regarding the total sum of all indicators. All numbers are absolute. The non-sustainability of resource management is shown by the deformed shape of the numerical relationship. Each axis "zero" value represents the wheel's center. The higher the quantity (higher level of sustainability) or the closest a point gets to the spoke's edge (high unsustainability level), the higher the quantity (higher level of sustainability).

## *3.2. Dynamics of VWC and WF of Crops*

From 2010 to 2019, the harvested area and crop yield increased in the GHA region, resulting in the increase in crops' WF (Figures 7 and 8). In 2016, crops such as barley, millet, and wheat registered a high WF of $7.08 \times 10^9$ m$^3$, $6.74 \times 10^9$ m$^3$, and $6.61 \times 10^9$ m$^3$ respectively. On the contrary, during 2010–2019, sorghum, maize, and millet showed a high average of VWC of 16.73 m$^3$·kg$^{-1}$, 16.66 m$^3$·kg$^{-1}$, and 10.02 m$^3$·kg$^{-1}$, respectively, compared to other staple crops such as wheat (8.56 $m^3 \cdot kg^{-1}$), rice (8.4 $m^3 \cdot kg^{-1}$), and barley (3.44 $m^3 \cdot kg^{-1}$). Rice and maize are the dominant food crops in the area, which use a little quantity of water and revealed a little embodied water in particular.

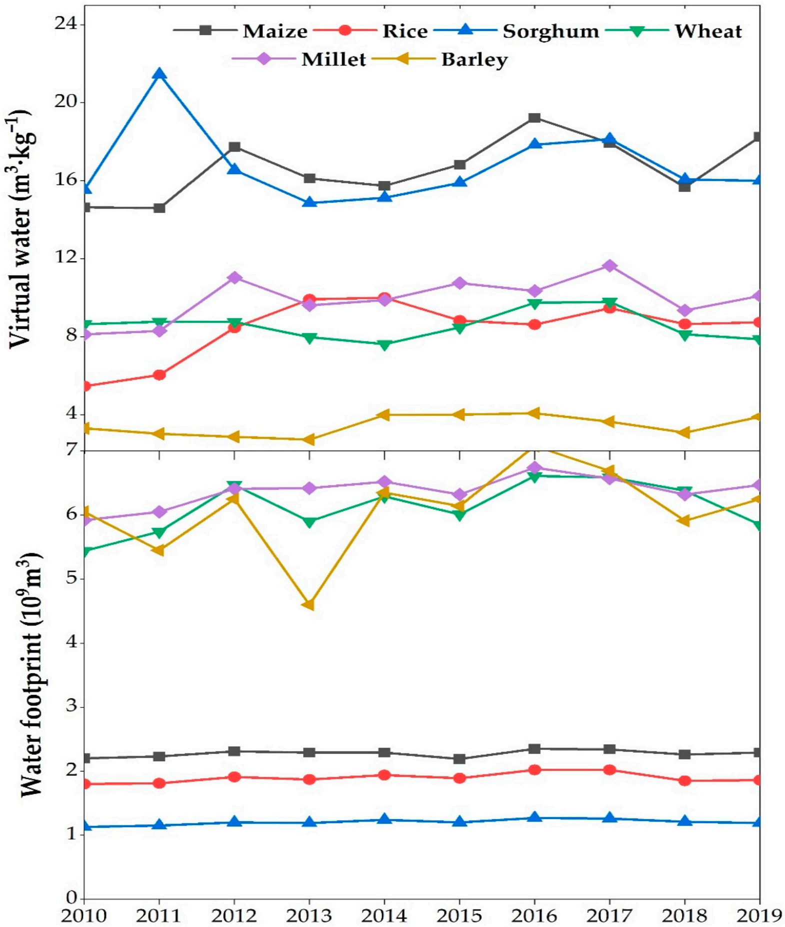


**Figure 7.** Dynamics of VWC and WF of the main staple crops in the GHA region from 2010 to 2019.

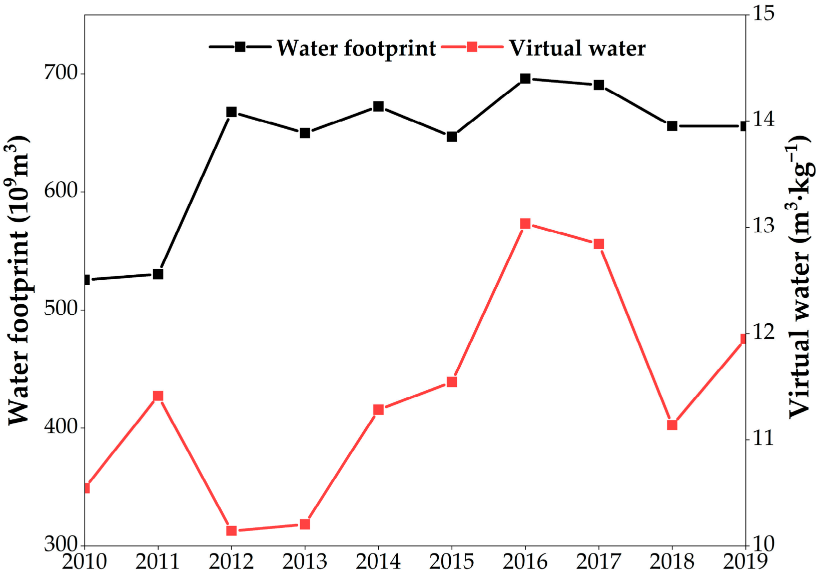


**Figure 8.** Overall changes of VWC and WF of crops in the GHA region from 2010 to 2019.

As the cultivated area is increasing, the total WF is also increasing. For example, in 2016 and 2017, the GHA region accounted approximately 696.1 × $10^9$ $m^3$ and 690 × $10^9$ $m^3$ of water consumed by the main crops, respectively, where the VWC depends on the type of crop and climatic conditions. However, these results indicated that countries like Sudan, Ethiopia, and Ethiopia, and Kenya have a higher WF.

## 4. Discussion

### *4.1. The WEFBH Nexus Tradeoffs and Synergies in the Lens of VW and Climate Change*

Water is intertwined with a variety of economic activities, and it has many diverse channels by which it influences human and economic development [102]. The advancement of the socioeconomic and environmental processes cannot work without the help of a long-term WEFBH scheme [103]. By considering water as a development enabler and emphasizing the interdependencies between water, energy, food supply, climate, and human health strategic systems, the WEFBH nexus offers a groundbreaking perspective on closing the energy-access gap, food security, biodiversity conservation, and human health development. Although several trade-offs and synergies within the WEFBH nexus such as water–food, water–energy, water–biodiversity, and water–human health can appear. Consider energy and food production, two important sectors where transfer, consumption, and production operations are regulated, resulting in food security, ecosystem function, and human health being jeopardized in the next decades. The WEFBH nexus is complex and interconnected, demonstrating the significance of the link process and maximizing synergies exchanges from a technological standpoint [104–106].

In the GHA region, rain-fed agriculture is the main sector [107]. However, during any period, dry spells can be just as damaging to crops as drought resulting in high crop water use [108]. It has a significant foundation for industry, water resources, and human well-being. In addition, using a high spatial resolution in arid areas, many studies found that among crops, maize had the lowest WF compared to wheat (high), and rice stood near the average [99,109]. Due to the drought (2012–2014), the study of Marston and Konar [110] showed a high WF because of high crop water requirements from higher temperature and a shift to more water-intensive crops, which negatively affect the VWC. Besides, during 2016–2017, Zwane [111] found that many agricultural dams had low water levels (i.e., 40%), which lead to crop failures. Therefore, irrigation extension is commonly used as a climate adaptation technique to keep food production going. The efficacy of irrigation expansion, on the other hand, is not transferable to areas where water supply is severely limited [112].

The quantitative results in Figure 6 presented are not intended to be forecasts, but rather to reveal the magnitudes of potential relative shifts, tradeoffs, or synergies from sectorial policies or strategies that may be of great interest to decision-makers and stakeholders, especially in relation to the SDGs. It is possible to investigate potential trade-offs and synergies, as well as techniques and organized resource management. According to Payet-Burin et al. [113], managing major irrigation expansions under climate instability and trade-offs with hydropower output is difficult. Extremely dry weather decreases hydropower and rainfed crop production, intensifying the trade-offs between irrigation and hydropower production, which can have negative consequences for human health.

### *4.2. Necessity of Linking of VW Concept and WEBFH Nexus, and Their Policy Implications*

The VW conception helps us understand how much water is needed to produce various products and services [114]. The WEFBH sectors are interdependent, have trade-offs, and have restrictive synergies, and thus play an important role in a region's long-term growth. Water, energy, food, biodiversity, and the human health system are closely linked, but in most cases, their management policies are separately formulated. The rivalry between the two tools is becoming more prevalent as a result of long-term separate management [115]. Combining water footprint analysis with food trade creates a network of traded or transferred VW resources [116]. Pairing VW trade with the WEFBH nexus under climate change provides future prospects for recognizing the burden shift of water scarcity globally.

Based on the result of the analysis, the following future policies were proposed:

① Incorporating the climate change and VW concept in WEFBH nexus: Climate change and VW trade incorporation into government decisions, initiatives, and policies is an effective way to promote climate action and reliable water resource management. Because there are several trade-offs and sometimes competing priorities when it comes to resource planning, reducing the impact of climate change by water management also includes politics. Even so, the importance of strengthening policy integration between mitigation, adaptation, and long-term growth should indeed be noted, through the creation of local markets and investment goods, as well as increased access to finance through international climate funds.

② Promoting the potentials to intensify water, biodiversity, human health-climate activity from the basin to regional level: The opportunities and priorities related to the VW and WEFBH sector in a changing climate, including ensuring water supply, sanitation, wastewater treatment, and managing disaster risks assessment.

③ Strengthening capacities of stakeholders and local government institutions: The local communities or stakeholders (e.g., national agencies, negotiators, regional and/or local government authorities, research institutions, and/or academia, etc.) will ultimately decide how the WEF nexus's trade-offs and synergies are implemented. This emphasizes the importance of local governments adopting and promoting nexus approaches, which include the planning structure for local public and private entities to make decisions. However, for the effectiveness of VW and WEFBH nexus decision-making, three key factors must be prioritized: (i) awareness of the connections between ecological and socioeconomic connections and other sectors, (ii) operational and professional capacity to apply nexus knowledge, and implementation of a nexus approach through horizontal and vertical coordination mechanisms.

④ Increasing the resilience of vulnerable communities through the construction of ecological civilization, and the retrogression mode of destroying the environment. The resource use efficiency should be improved to reduce waste, and circular-economy-based investment and policy should be increased.

⑤ Enhancing data, research, and innovation: It is in need of collated datasets on water, energy, food, ecosystem, and human health-related sectors that can provide the regional extent of quantity and quality data. Climate-adaptive creative strategies, creation, and use of adaptation monitoring tools and metrics can be handled by both public and private organizations.

### *4.3. Future Directions in VW and WEFBH Nexus Studies*

The present study used the MCDM through the AHP approach to assessing the performance of WEFBH nexus indicators and VW components. The selection of areal indicators widely facilitates the selection of a policy option in detail, whereas AHP applications are extensive, for instance within the Africa context, and sustainability is still rare [117]. Predominantly in regional studies, like this one, combining several variables, finding a single and suitable analysis methodology is difficult. Therefore, ranking irregularities can occur when the AHP variants are used [118].

Therefore, this study employed simple procedures [119] to assess the WF, NVWIs of the GHA countries. Although this research study strives to develop our understanding and quantification of WFs, a possible challenge compromised of a discussion about customer decision-making emerges [120]. For instance, the concepts and methods of coupled natural-human systems (CNH) and Embedded Resource Accounting (ERA) were proposed by several authors [2,121] in the domains of WF and the water–energy nexus, thereby estimating the VW flow in the electric power sector and exposed the relationship between the water resource networks and the electric power system, and provided suggestions for decision-makers and managers. However, further VW researches still need to be improved and perfected with more advanced data and needed in terms of assessing regional interrelations on various scales. The prediction and driving factors analysis of VW need further research, and the availability and accuracy of data still need to be ensured to interconnect VW-related disciplines involving hydrology, socio-economy, and ecological environment. Future researches should be conducted in conjunction with relevant knowledge in other disciplines to alleviate regional water shortage.

Recently, there has been a tendency to explore the WEF nexus itself from different temporal and spatial scales. Future analysis of the WEFBH nexus would benefit from exploring other possibilities of assessments and their impacts on the findings. We argue that studies linking VW and WEFBH nexus in the face of climate change cannot be ignored in Africa's arid areas. Therefore, in future studies, the criteria for sustainability could be looked into in more detail, to better take into account all driving factors of sustainable development.

### 4.4. Research Limitations

This study has potential limitations and did not include the overall sustainability indicators. The present study mostly faced bottleneck challenges while choosing the right indicator to decide at the right time [78]. However, the election of the indicators was based on the indicators that directly contribute to the performance of the WEFBH nexus and VW concept. However, the SDGs of the UN have some indicators that look similar. For that case, we ignored one and prioritized another. For instance, in food insecurity indicator selection, this study considered the prevalence of undernourishment (%) and cereal yield (tons per hectare of harvested land) instead of all global hunger index indicators. There is a lack of the same time series for the indicators. Despite the best attempts to gather information for SDGs indicators, some uncertainties persist [86].

Furthermore, though VW research has attained many findings, there are still some limitations [122]. For example, some important food categories (e.g., agricultural and livestock processed products) were not considered or differentiated. This study was not based on field assessments of water footprint; we did not consider any ecological issues caused by water consumption. The secondary data presented some flaws from one dataset to another. We encountered a lack of updated data and high-quality data for some areas, for example in Burundi, Djibouti, South Sudan, and Eritrea. Therefore, this study recognizes all uncertainties in measurement accuracy and precision that may have risen during indicators selection, VW, WF, and WEFBH nexus factors estimations.

Indeed, with the AHP model, foundational data information may be lost, competing indicators may be discarded, and uncertainty aspects may be overlooked [34]. Moreover, the preference for any criterion does not depend on the values of the other criteria. As a consequence, Different components may result in varying final rankings. We discovered that criteria with a big set number of sub-criteria tend to obtain further weight than criteria with fewer sub-criteria. So far, we have clustered these indicators in clusters so that they do not differ in awful ways. Although, the pairwise comparisons were subjected to judgmental errors and are inconsistent and conflicting with each other. Ultimately, when the CRs are above 0.1, we re-evaluated the normalized PWC matrix to make sure it is reliable.

## 5. Conclusions

Water is the crucial criterion for environmental and socioeconomic advancement; it also provides the basis for healthy ecosystems and the human wellbeing of any region or country. This study presents the first comprehensive insight on the complex interlinkages and interdependencies between VW and WEFBH sectors under a changing climate and formulating the essential and effective policies for sustainable development. This study also highlighted the significance of VW trade in achieving sustainable water resources management. Currently, the GHA region is categorized as one of the world's most food-insecure regions, while containing many resources for energy and food production. This area is not self-sufficient in the case of food and thus relies on agricultural imports.

Despite that, the WF of crops indicated a temporal increase during 2010–2019. Rice and wheat are the dominant food crops in the GHA region proved to use a little amount of water. Much effort (about 63.0% of achievement) has been done for promoting sustainable natural resource use in the case study. However, most countries in the GHA region are facing WEFBH resource unsustainability due to weak planning or improper management strategies. These resulted in persistent food insecurity, lack of electricity, good water quality for drinking, and other environmental issues. In view of the above-mentioned issues, it is necessary to adjust the water, energy, food, biodiversity, and human health evidence-based strategic policy in every GHA country member, and at the same time consider the valuation of the amount VW in every level of production, and enhance the development of other alternative sources of renewable energy such as thermal power, solar power, hydropower, and wind power).

Lastly, as a step forward for this study, we sum up two crucial questions as suggestions to promote integrated policy approaches: (1) What are the relevant water accounts at the basin scale and their contribution to the WEFBH nexus? (2) What strategies can be implemented on the crosswise use management rather than the supply management side to reduce the water footprint within WEFBH sectors under climate change? As the literature on the water footprint, VW, and WEFBH nexus grows, we subsequently pose this closing question. With this raising consciousness, there is a need for a shift in policy analysis to transcribe literature recommendations to decision-making frameworks at all stages of production and evaluate burden shifts of the water resource and climate change.

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