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Research Article

Quantifying Water-Food Nexus (Water Footprint) for Food Crop Production: A Case Study of Addis Ababa City

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Analyzing the water–food nexus is the first step in examining the decision-making process in planning and evaluating urban policies that consider the nexus. The main purpose of this research is to create a tool for decision makers to analyze and quantify the water–food nexus of urban agricultural food crop production. Using the proposed strategy, indicators for water consumption and water footprint productivity were provided. A water–food nexus was created using these indicators. Annual water demand indicators for potato, tomato, onion, and cabbage were calculated to be around 9070, 9330, 6240, and 8230 m^3/ha, respectively. The computed water consumption indicator of vegetable crops ranged from 6240 to 9330 m^3/ha, according to the study. When compared to other food crops, onion has the lowest water consumption indicator. The water-food nexus in agricultural food crop production can be used as a comprehensive instrument to assess progress in city water and agricultural initiatives. It might also be used to analyze the performance of water-food nexus management on a yearly basis.

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1. Introduction

Water and food are fundamental pillars of human existence and development. Their interdependence—often referred to as the water-food nexus—is critical for effective resource management and sustainable development. As the global population increases and the impacts of climate change intensify, the competition for water and food resources is becoming more pronounced. This interconnectedness has garnered significant attention in scientific and policy discussions, particularly in light of uncertainties regarding access to these essential resources[1].

The water-food nexus is pivotal in addressing global challenges such as food security and water scarcity. It is particularly relevant in urban settings, where the demand for food and water is high. Urban areas are increasingly recognized as major consumers of resources, which intensifies the need for integrated management strategies that consider both water and food systems.

The challenges associated with managing the water-food nexus are multifaceted. Climate variability, population growth, and changing consumption patterns strain the availability of both water and food resources. These challenges necessitate innovative management approaches that can optimize resource use and ensure sustainability. Quantitative models play a crucial role in this context, as they provide insights into the complex interactions between water and food systems[2]. Several models have been developed to explore these interactions, highlighting the need for effective tools that can guide policy and resource management strategies[3].

Despite the increasing recognition of the water-food nexus, a notable gap remains in quantitative assessments of these interconnections. Many existing studies emphasize qualitative analyses, which, while valuable, do not provide the detailed insights necessary for effective policy design. Quantifying the relationships between water and food is essential for enhancing urban water and food security, as well as promoting sustainable agricultural practices[2]. This study aims to bridge this gap by providing a comprehensive quantitative assessment of the water-food nexus in the urban context of Addis Ababa.

In agricultural contexts, the water-food nexus is often operationalized through the concept of the water footprint. This metric quantifies the volume of water used in food production, specifically the irrigation water consumed for different crops. It is defined as the total water consumption associated with crop yield[4]. The assessment of the water-food nexus through crop water footprints provides valuable insights into the volume of water required for crop growth relative to yield[5]. This approach is instrumental in evaluating water consumption in agricultural production and can help identify opportunities for improving water use efficiency.

This study aims to quantify the water requirements for food crop production in the urban area of Addis Ababa, focusing on four specific crops: potato, tomato, onion, and cabbage. Utilizing the FAO Penman-Monteith (FAO-PM) method, facilitated by the CropWat model, the study seeks to estimate the water consumption associated with these crops. Furthermore, it aims to establish a baseline for the urban water-food nexus by examining indicators such as water usage per hectare and overall water footprint.

2. Methodology

2.1. Data

This study utilized a comprehensive dataset spanning seven years (2010 to 2016), sourced from the National Meteorological Service Agency (NMSA) at three meteorological stations: Observatory, Akaki, and Bole. The key meteorological variables collected include:

- Maximum Temperature (T_{max})
- Minimum Temperature (T_{min})
- Sunshine Duration (n)
- Wind Speed (u_z)
- Maximum Relative Humidity (RH_{max})
- Minimum Relative Humidity (RH_{min})

Additionally, the spatial distribution of the four primary crops (potato, tomato, onion, and cabbage) along with their respective yields was obtained from the Addis Ababa Agricultural Office.

a. Temperature

The average monthly maximum and minimum temperatures of the three stations are indicated in Figure 1.

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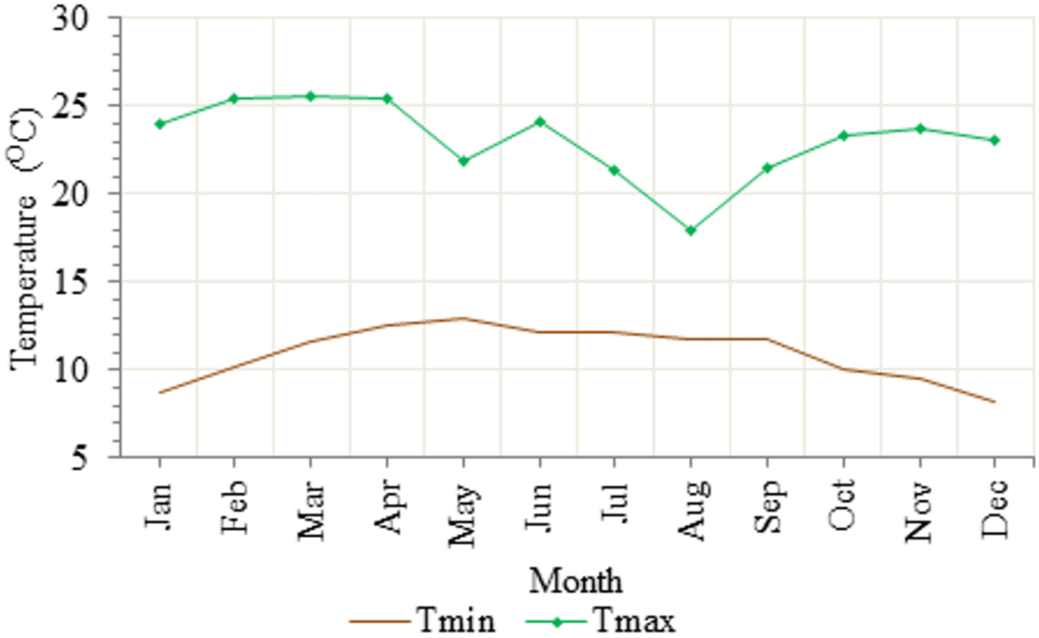

Figure 1. Average annual monthly temperature for three stations (OBS, Akaki, and Bole) (Source: NMSA)

b. Wind speed and sunshine

The data revealed that the highest average wind speeds were recorded in February (0.9 m/s) and March (1.0 m/s), while the lowest occurred in August (0.5 m/s). Sunshine duration peaked in December (9.1 hours) and was at its minimum in July (3.1 hours). The average annual wind speed and sunshine duration for Addis Ababa were 0.8 m/s and 6.7 hours, respectively, as shown in Figure 2.

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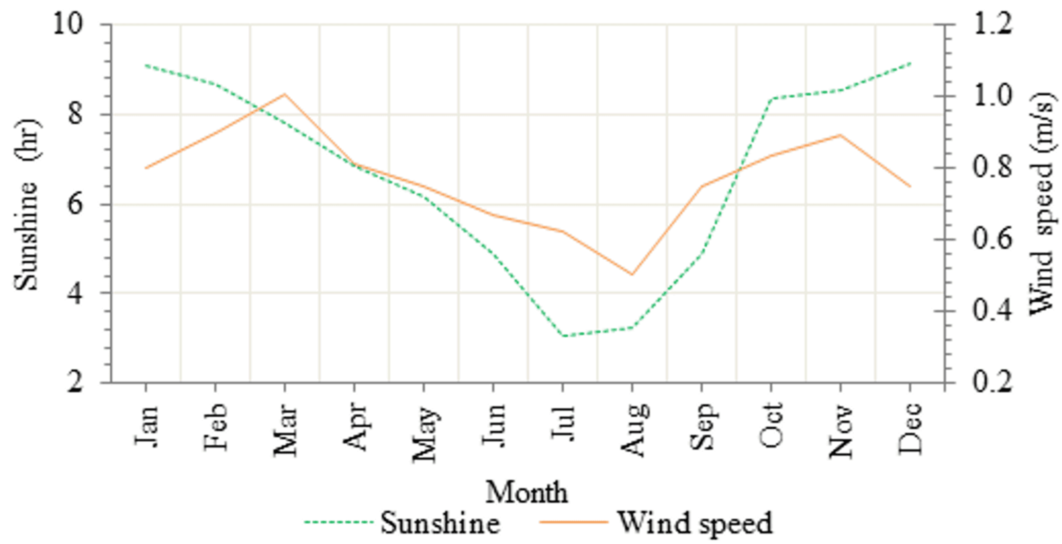

Figure 2. Average monthly wind speed and sunshine (2010-2016) (Source: NMSA)

c. Precipitation and relative humidity

Precipitation and relative humidity are critical factors influencing crop growth. During the period from 2010 to 2016, the average relative humidity in Addis Ababa was 58%. The highest relative humidity was observed in August (75%) and July (73%), whereas February recorded the lowest (46%). The average annual total rainfall across the three stations was approximately 1012 mm, with the wet season occurring from June to mid-September and peak precipitation in July and August. Monthly variations in precipitation and relative humidity are detailed in Figure 3.

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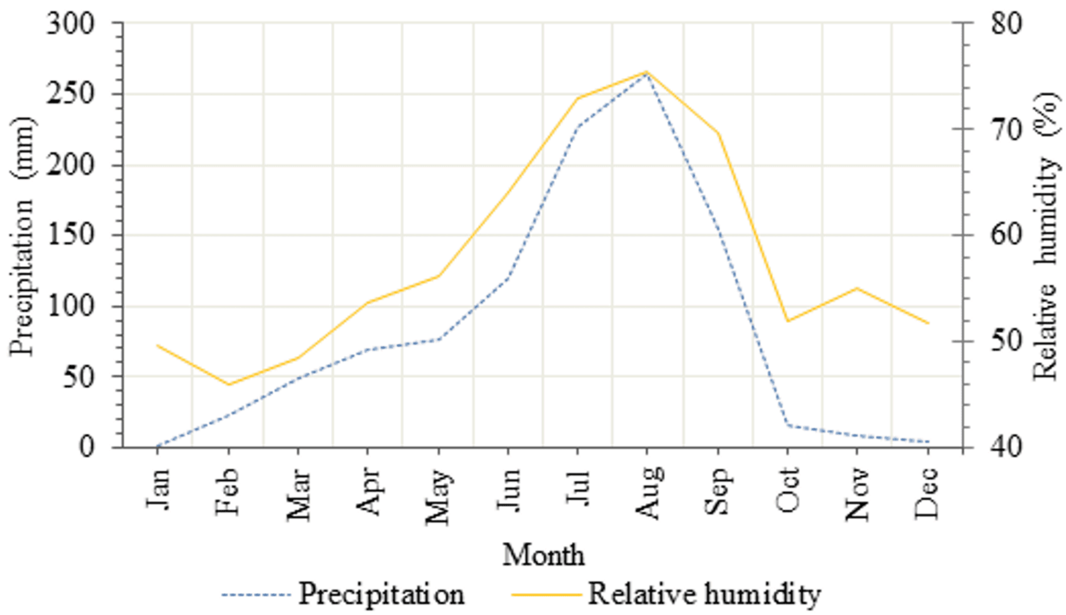

Figure 3. Monthly average RH and precipitation (2010-2016) (Source: NMSA office)

The CropWat model was employed to calculate crop evaporation using the collected climate data, which is compatible with the Penman-Monteith (PM) method. This approach allows for accurate calculations of crop water requirements[6]. The PM method requires several parameters, including monthly maximum and minimum temperatures, wind speed, mean relative humidity, and sunshine hours[7].

Further, data on soil and crop characteristics for tomato, onion, cabbage, and potato were sourced from FAO guidelines[7]. This included parameters such as root depth, crop coefficients (Kc), critical depletion, yield response factor, and length of growth stages. Planting dates were based on agricultural operations outlined by the Addis Ababa Agricultural Office. Effective rainfall calculations utilized the seven years of rainfall data from the three stations, employing the USDA Soil Conservation Service (USDA SCS) method within the CropWat model[6].

d. Crop area and yield

The crops considered (potato, tomato, onion, and cabbage) are predominantly cultivated in the upper and middle sections of the Akaki River basin. Data regarding the cultivated land area (in hectares) and yield (in tons) for each crop were obtained from the Addis Ababa Agricultural Office, forming the basis for estimating the water-food nexus. The agricultural food production per unit area was calculated by multiplying the land area by the yield, as depicted in Figure 4.

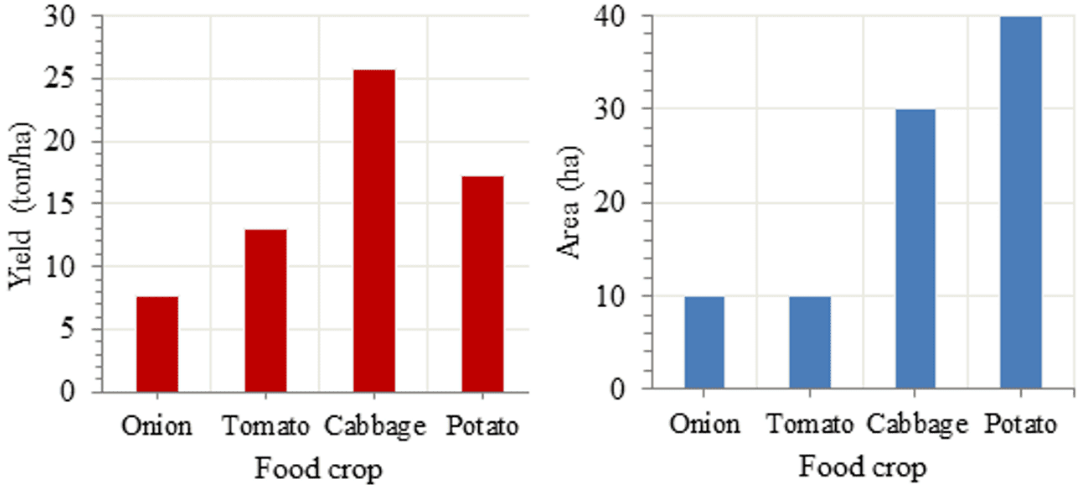

Figure 4. Planting area and yields of crops (Source: Addis Ababa agricultural office)

2.2. Water-food nexus framework and parameters

This study proposed two primary indicators to quantify the water-food nexus within the crop production system:

1. **Water Demand or Consumption Indicators:** Annual water demand or consumption per hectare of crop.
2. **Water Footprint Indicators:** Yield of crop per unit of water consumption or demand.

These indicators allow for a comprehensive assessment of the water-food nexus, as illustrated in the computation framework in Figure 5.

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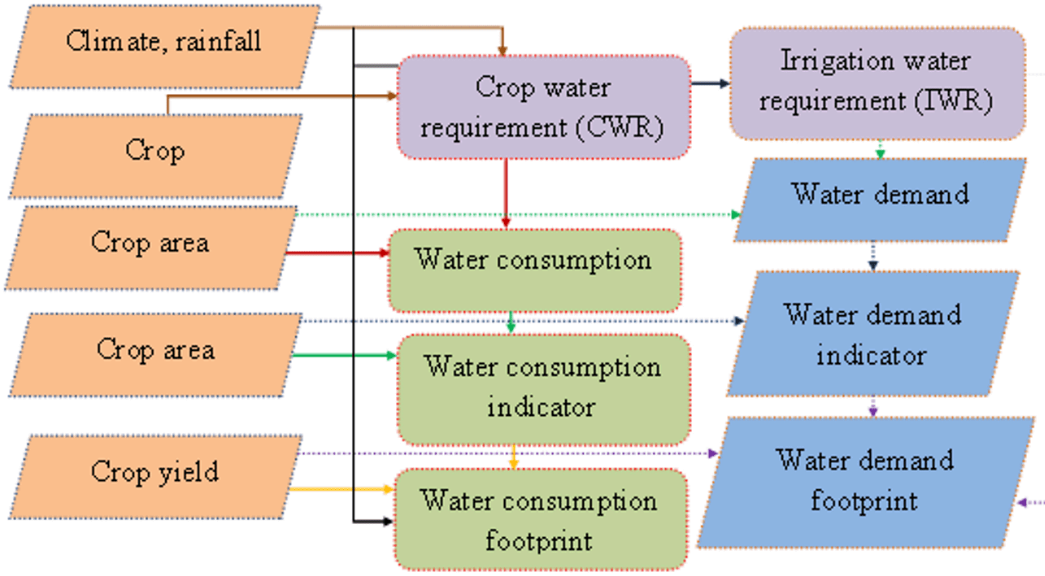

Figure 5. Computation framework of water-food nexus indicators

The framework facilitates the quantification of water requirements in food crop production, informing strategies for improved resource management, as outlined in Figure 6.

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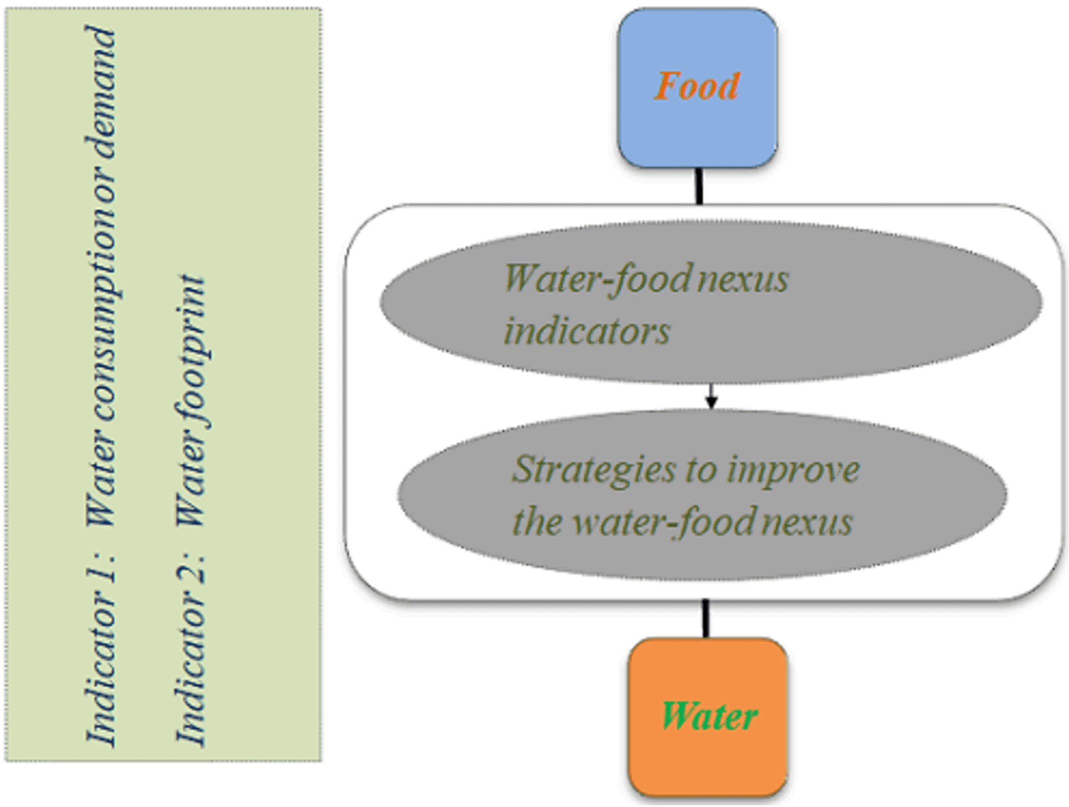

Figure 6. Water-food nexus assessment indicators of agricultural food production[8]

The initial step in calculating the water footprint for food crop production involves estimating ETo. The FAO model provides a robust framework for assessing the water requirements of agricultural crops based on soil, climate, and crop data. Its advantages include reduced data requirements compared to more complex models[9].

The FAO Penman-Monteith method is widely regarded as the standard for determining ETo, yielding accurate and consistent results for crop water use globally (FAO, 1992). The rate of evapotranspiration (ET) from a hypothetical crop with defined characteristics is represented as ETo. The ETo was calculated as given by Eq (1).

$$ET_o = \frac{0.408\Delta\left(R_n - G\right) + \gamma\left(\frac{900}{T+273}\right)U_z\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34u_2\right)} \quad (1)$$

Where:

- Δ = slope of the vapor pressure curve (kPa/°C)
- R_n = net radiation (MJ/m²/d)
- G = soil heat flux (MJ/m²/d)
- γ = psychrometric constant (kPa/°C)
- U_z = daily mean wind speed at 2 m height (m/s)
- e_s = saturation vapor pressure (kPa)
- e_a = daily mean actual vapor pressure (kPa)

The net radiation was computed using:

The net radiation was calculated as follows using Eq (2).

$$R_n = 0.77\left(a + b\frac{n}{N}\right)R_a - R_{nl} \quad (2)$$

Where a and b are constant coefficients (a = 0.18 and b = 0.55); n is the sunshine duration (hr); N is the maximum sunshine duration (hr); R_a is the extraterrestrial radiation (MJ/m^{2}d); and R_{nl} is the net outgoing longwave radiation (MJ/m^{2}d)[10].

2.3. Consumption perspective water-food nexus

The crop water requirement (CWR) is the amount of water equal to what is lost from a cropped field by the crop evapotranspiration (ET_c) and is expressed as a function of ET_c and effective rainfall (P_{effe}). These two variables can be measured in millimeters (mm). The CWR is computed as follows by Eq (3).

$$CWR = ET_c - P_{effe} \quad (3)$$

The CWR approach is based on the crop coefficient (K_c) to calculate the ET_c (mm) of each crop for the meteorological stations[11]. It is computed using Eq (4).

$$ET_c = K_C \ X \ ET_o \quad (4)$$

The K_c value is affected by climate, soil evaporation, crop type, and crop growth stages[12]. Due to the ET differences during the growth stages, the K_c value of the crop is varying over the developing period that can be categorized into four distinct stages (initial, development, mid, and late)[9]. The Kc value for four distinct stages of different crops considered in this study is indicated in Figure 7.

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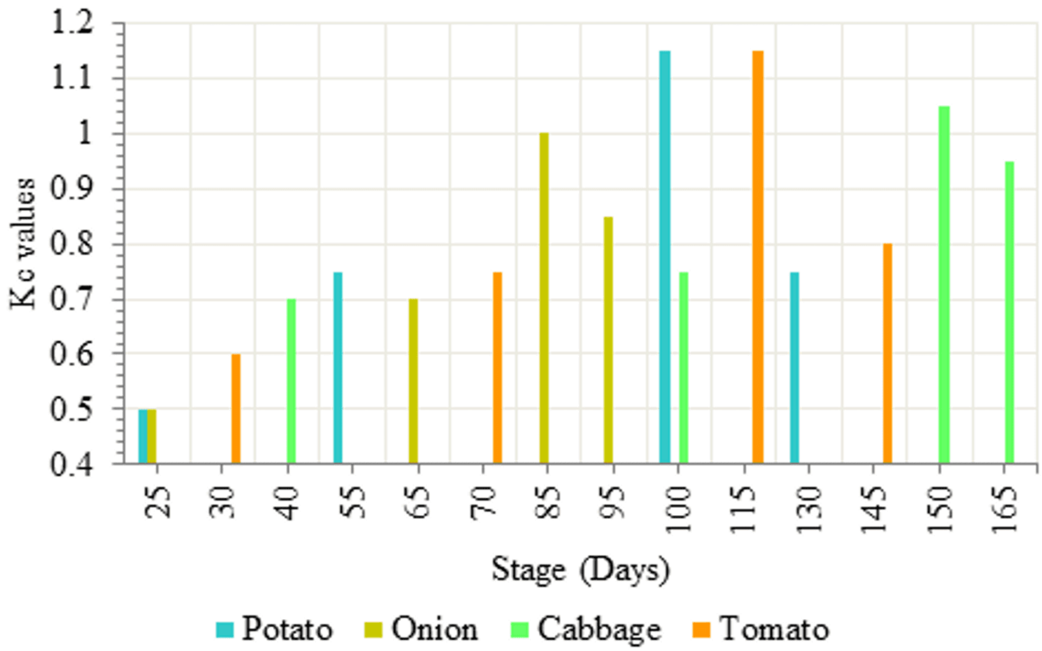

Figure 7. The K_c for different growing stages of different crops[9].

The USDA SCS method is used to estimate the P_{effe} considering the precipitation (P). According to this method, Eq (5) and Eq (6) are used to compute P_{effe} (mm) from P (mm).

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$$P_{effe} = \frac{P\ (125 - 0.2\ \times 3\ \times\ P)}{125} \qquad for\ P \leq\ \frac{250}{3} \tag{5}$$

$$P_{effe} = \frac{125}{3} + 0.1 \times P \qquad for\ P >\ \frac{250}{3} \tag{6}$$

Water consumption (W_c) indicator: It is the water consumption per hectare of the crop (m^3/ha) and is calculated considering CWR (mm) and crop area (A_c) in hectares (ha) as indicated in Eq (7).

$$W_c =\ \frac{CWR}{A_c} \tag{7}$$

Water consumption footprint ($W_{fp,c}$) indicator: Water footprint (m^3/ton) is calculated by applying Eq (8) using a yield of the crop (Y_c) (ton/ha) and W_c (m^3/ha).

$$W_{pro}\ =\ \frac{Y_c}{W_c} \tag{8}$$

Total water consumption ($W_{t,c}$): Total water of the production of crop per year (m^3/year) is calculated based on A_c (ha) and \(W_{c}\\)(m^3/ha) according to Eq (9).

$$W_{t,c} =\ \sum_{c=1}^{v} A_c\ \times\ w_c \tag{9}$$

2.4. Demand perspective water-food nexus

Crop water demand or irrigation water requirement can be computed using Eq (10).

$$IWR =\ \frac{S\ X\ CWR}{I_C} \tag{10}$$

Where IWR = irrigation water requirement of certain crops (m^3), S = area of the crop (ha), Ic = irrigation efficiency or field efficiency which is taken as 60% for Akaki catchment[13].

Water demand (W_d) indicators: It is the water demand per hectare of the crop (m^3/ha) and is calculated by applying Eq (11) by considering IWR (m^3) and A_c (ha).

$$W_d =\ \frac{IWR}{A_c} \tag{11}$$

Water demand footprint ($W_{fp,d}$) indicators: Water footprint (m^3/ton) depends on the yield of the crop (Y_c) (ton/ha) and W_d (m^3/ha). It is calculated by applying Eq (12).

$$W_{pro}\ =\ \frac{Y_c}{W_d} \tag{12}$$

Total water demand ($W_{t,d}$): This is the total water of the production of the crop per year (m^3/year) and is calculated using the cultivated area of the crop (ha) and the water demand indicator (m^3/ha) by Eq (13).

$$W_{t,d} =\ \sum_{c=1}^{v} A_c\ \times\ W_d \tag{13}$$

Through this comprehensive methodology, the study aims to quantitatively assess the water-food nexus in food crop production within Addis Ababa, providing valuable insights for resource management and policy development.

3. Results and discussion

This study estimates water-food nexus indicators in the urban food production system for long-term resource planning. The FAO-PM method, with the help of the CropWat model, is used to determine the amount of water needed in the food production system. The results of unit water required per food production and per land as a water-food nexus indicator of crop production are obtained.

3.1. CWR, IWR and ET_c

The average annual precipitation that was considered in the estimation of effective rainfall is around 1012 mm. Effective rainfall is the part of precipitation that is effectively used by the crop after losses by runoff and deep percolation; it was used to compute the crop water consumption or crop water requirement. The annual average ET_0 and effective rainfall were estimated as 1321 and 734 mm, respectively.

The losses occur during the transport of water to irrigation land; therefore, the determination of IWR is needed for consideration of losses or efficiency. Having efficiency, water consumption is converted to irrigation water requirement. Based on the calculated CWR, the IWR was estimated. The value used in the computation of the water-food nexus indicator for each crop category is given in Figure 8.

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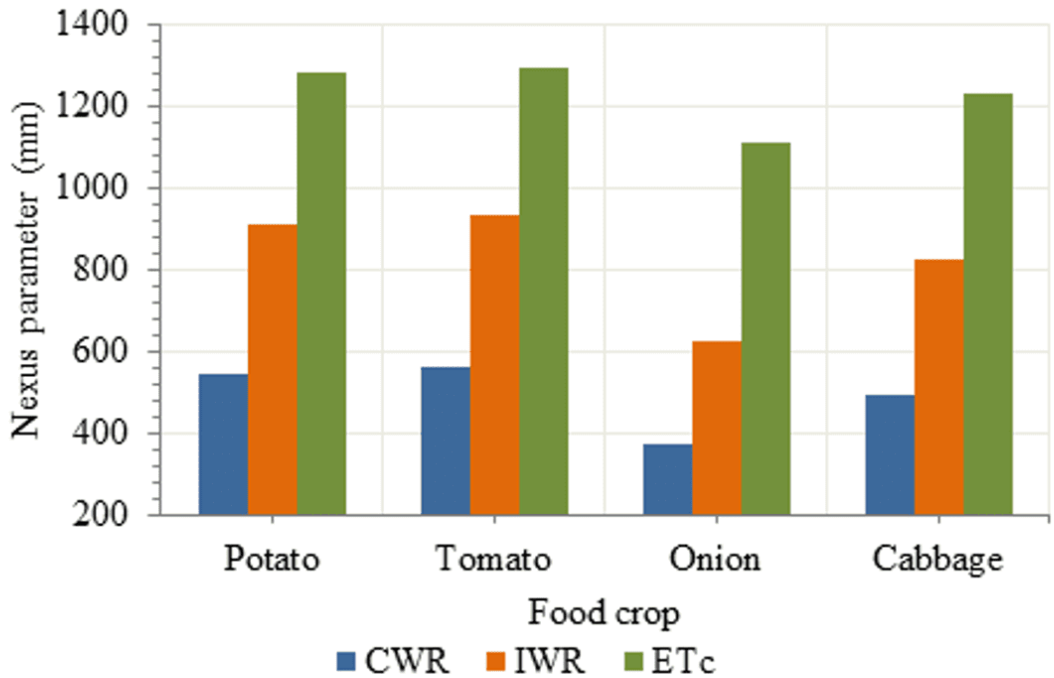

Figure 8. Annual value of water-food nexus indicator parameters for different crops

3.2. Amount of water use for food crop production

The value of the water use for each crop in 2016 accounted for about 362800, 93300, 62400, and 246900 m^3 for potato, tomato, onion, and cabbage, respectively. The total water use of crops is the sum of the water use of the individual four crops (potato, tomato, cabbage, and onion), which is 767 and 460 x 10^3 m^3 for gross and net, respectively. This indicates that the total water consumption for the production of four food crops in 2016 was about 460 x 10^3 m^3 (47, 8, 32, and 12% were used by potato, onion, cabbage, and tomato, respectively). The annual water consumption and demand in 10^3 m^3 for each crop are shown in Figure 9.

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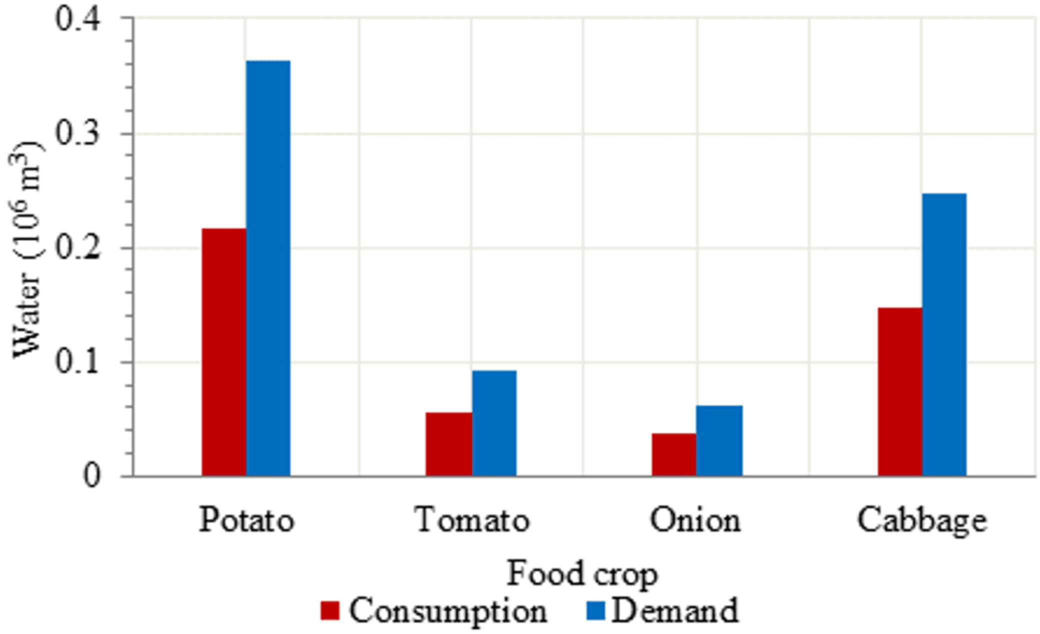

Figure 9. Estimated water use for categories of crops

Figure 9 showed that the water consumption for all vegetables is smaller than the water demand because the former measures the net amount of water used for each vegetable crop produced, whereas the latter measures the overall water demanded.

3.3. Water use indicators

The annual water demand indicator, which is the volume of water per area of cropland for potato, tomato, onion, and cabbage, is 9070, 9330, 6240, and 8230 m^3/ha, respectively. The annual water consumption (W_c) indicator per hectare for tomato, potato, onion, and cabbage was about 5600, 5440, 3740, and 4940 m^3/ha, respectively. This is comparable to other studies. Tadesse et al.[14] estimated annual water consumption for tomato, potato, onion, and cabbage as 5130, 5650, 5400, and 5830 m^3/ha, respectively. These insignificant result variations can be due to the spatial and temporal variation of input datasets like climate datasets, methods and/or tools adopted, and others such as planting date, etc.

3.4. Water footprint indicators

Another indicator in this study is the water footprint. This index is mainly influenced by two factors: water input and crop yield. Each kind of crop with higher water consumption has a higher water footprint than other crops (Figure 10). The annual water demand footprint for potato, tomato, onion, and cabbage is 527, 718, 820, and 320 m^3/ton, respectively, whereas the water consumption footprint is 316, 430, 492, and 191 m^3/ton. The water consumption footprint for all vegetables is less than the water demand footprint since the prior one measures the amount of water used per unit crop produced, whereas the latter measures the gross water required per unit crop produced.

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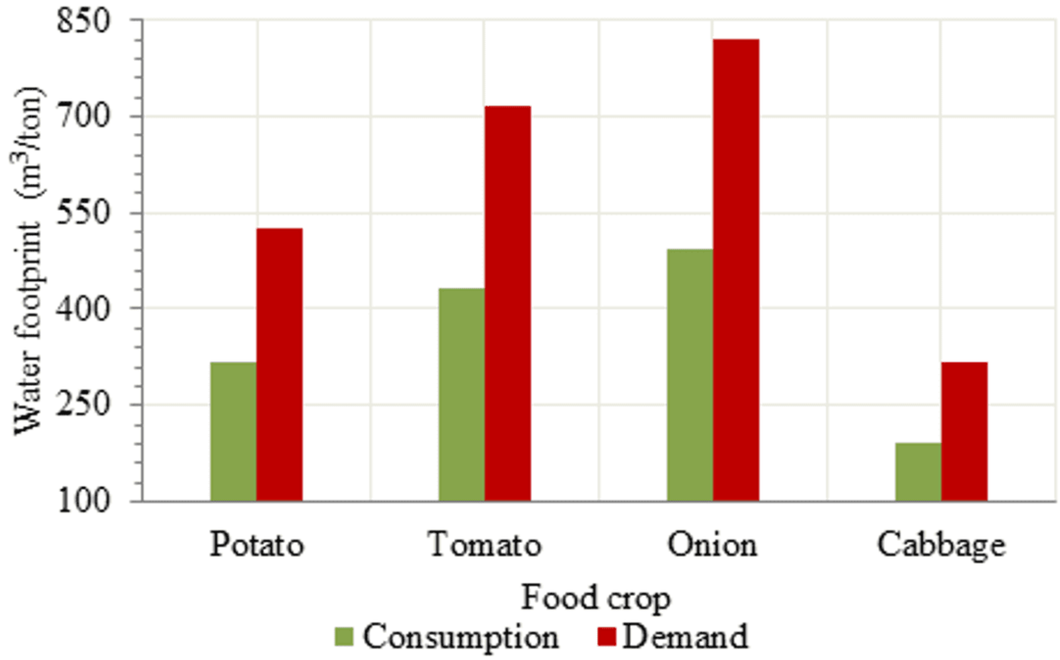

Figure 10. Water footprint indicators for different food crops

More water footprints of the crop mean larger water consumption and smaller yield in the growth period. The average volume of water per ton of primary crop has differed significantly among crops. The water consumption footprint for onion production was highest, i.e., 492 m^3/ton, while the lowest amount of water footprint was used for cabbage (191 m^3/ton). These estimated water footprints are within a range of global values, which is 200-300 m^3/ton for vegetables and 500-1000 m^3/ton for fruit[15]. Generally, the average total water consumption footprint for the production of the four crops at the study catchment is 358 m^3/ton. Figure 11 shows the contribution of the crops to total yield and the water footprint indicator.

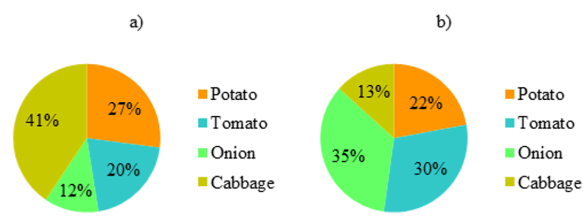

Figure 11. Contribution of crop input categories to (a) total crop yield (ton/ha) and (b) total water footprint (m^3/ton)

From a and b of Figure 11, onion has the highest percentage of water footprint (35%) but the least contribution to yield (12%); on the contrary, cabbage has the least water footprint (13%) but the maximum for yield (41%).

4. Conclusion

This study aims to analyze and quantify the baseline water-food nexus in urban food production systems by applying the water-food nexus indicators. These indicators are major concerns that integrate urban water-food for resource management and planning.

The indicators are highly relevant to both the water and food sectors and to the sustainable management of water and food productivity. This water footprint metric is essential for calculating the water demand. The two aspects of the indicators were considered as water consumption or demand per unit area of land (m^3/ha) and water footprint (m^3/ton). Indicators are influenced by cropland area, crop productivity, production, and water consumption. Water consumption and demand were estimated based on the PM-FAO approach, which is widely accepted due to its accuracy and the availability of input data.

The findings are from 2016, and the total water demand for potato, tomato, onion, and cabbage was 362.8 x 10^3, 93.3 x 10^3, 187.2 x 10^3, and 82.3 x 10^3 m^3, respectively. In terms of the proportion of agricultural irrigation water (water consumption indicator), tomato consumed the most (5600 m^3/ha), followed by potato, cabbage, and onion at 5440 m^3/ha, 4940 m^3/ha, and 3740 m^3/ha, respectively. The result also showed that the water demand per hectare for potato, tomato, onion, and cabbage was 9070, 9330, 6240, and 8230 m^3/ha, respectively. In this study, the water footprint provides direction to manage water consumption. The result showed that the water footprint decreases when the yield increases, which indicates an inverse proportionality relationship.

The present water-food nexus indicator method can effectively utilize and provide pertinent baseline data in determining the water requirements of urban food crop production such as onion, tomato, cabbage, and potato. Since the method gave acceptable values, one can easily use the method implemented in this study to predict the urban water-food nexus indicators. It is useful to analyze linkages between water and food in urban food production. Quantifying water-food connections is important for integrated water-energy-food nexus modeling and management. In addition, quantifying and understanding the water-food nexus from the viewpoint of the water footprint, and the volume of water required per area of land as a nexus indicator, are important concepts in urban water management.

Further development can be conducted on the following issue: Sound decision-making and solutions to the water-food nexus in crop production are based on science, which is backed up by data of adequate quality and detail. Because the water uses for food production are not metered, water-food nexus indicators data for food production is mostly reliant on models and proxies. Due to a significant reduction in incoming data delay, water footprint calculations can be employed for real-time decision-making.

Statements and Declarations

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Data Availability

All relevant data are within the manuscript.

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Conflicts of Interest

The authors have declared that no competing interests exist.

Author Contributions

- **Conceptualization**: Bedassa Dessalegn Kitessa, Semu Moges Ayalew, Geremew Sahilu Gebrie, Solomon T/mariam Teferi.
- **Data curation**: Bedassa Dessalegn Kitessa, Geremew Sahilu Gebrie.
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- **Methodology**: Geremew Sahilu Gebrie.
- **Supervision**: Semu Moges Ayalew.
- **Validation**: Semu Moges Ayalew, Geremew Sahilu Gebrie.
- **Visualization**: Semu Moges Ayalew, Geremew Sahilu Gebrie, Solomon T/mariam Teferi.

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Declarations

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