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# Assessing the per capita water footprint of crops in Egypt and calculating the virtual water imported and exported

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**Abstract:** The current research aims to calculate the water footprint of Egyptian crops, estimate the water footprint per capita from the crops under study, and determine the percentage of dependence on external water sources versus self-sufficiency. Additionally, the study assesses the national self-sufficiency of water available for agriculture and Egypt's total exports and imports of virtual water for the crops under examination.

Monthly weather data was sourced from NASA from 2019 to 2022. The Crop-Wat model was utilized to calculate both green and blue water footprints. The water footprint of 59 crops was analyzed, encompassing a range of field crops and vegetables cultivated during Egypt's winter, summer, and Nili seasons. However, due to insufficient export and import data for certain selected crops, the research narrowed its focus to 25 crops for which this data is available, enabling the pursuit of the study's other objectives. The results indicated that the average total water footprint during the study period was 508, 275, 1578, 385, and 563 m³/ton for the respective crop groups: winter field crops, winter vegetables, summer field crops, summer vegetables, and Nili crops. The overall average was 662 m³/ton. Regarding the average water footprint per capita in Egypt for the studied crops, wheat, maize, and soybeans had the highest values at 130, 163, and 104 m³/capita/year, respectively. The study noted that the percentage of dependence on external virtual water versus self-sufficiency registered the highest values for soybeans (99%), dry faba beans (85%), sunflower (79%), wheat (55%), and maize (54%). Most vegetable crops achieved national self-sufficiency and even surpassed it, with some being exported. Finally, the research revealed that Egypt's total virtual water exports for the studied crops amounted to 231 million m³, while imports reached about 27 billion m³.

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**Keywords:** Green-blue water footprint; Egyptian crops; National Water Self-Sufficiency; National water dependency versus water self-sufficiency

## 1. Introduction

The growing global population, enhanced living standards, evolving consumption patterns, and the expansion of irrigated agriculture are the key factors driving the increase in global water demand (Ercin and Hoekstra, 2014). Approximately 1.8 to 2.9 billion people experience severe water scarcity for at least 4 to 6 months yearly. Additionally, around half a billion people face severe water scarcity year-round. Among those, 180 million reside in India, 73 million in Pakistan, 27 million in Egypt, 20 million in Mexico, 20 million in Saudi Arabia, and 18 million in Yemen. In Saudi Arabia and Yemen, the entire populations of these countries are affected, placing them in an extremely vulnerable position. Other nations with a significant portion of their populations experiencing year-round severe water scarcity include Libya and Somalia, where 80 to 90% of the population is affected, as well as Pakistan, Morocco, Niger, and Jordan, where 50 to 55% of the population faces similar challenges (Mekonnen and Hoekstra, 2016).

The agricultural sector in Egypt is the largest consumer of water, which makes effective management of this vital resource essential. Effective water management is essential for securing a sufficient water supply and ensuring food security for the population. Properly managing water resources is vital to address the limited availability in these areas and to achieve sustainable development, food security, and stability (El-Marsafawy and Mohamed, 2021).

In 2002, the water footprint (WF) concept was introduced to provide a consumption-based indicator of water use, offering additional insights beyond the traditional production-sector-based indicators

(Hoekstra and Hung, 2002). A nation's WF is defined as the total volume of freshwater used to produce the goods and services consumed by its residents. Since not all goods consumed in a particular country are produced domestically, the WF comprises domestic water resources and water imported from outside the country's borders. The Water Footprint (WF) consists of three components: green, blue, and grey water footprints. The blue water footprint represents the volume of surface water and groundwater that is consumed or evaporated during the production of a product. The green water footprint refers to the amount of rainwater consumed. Lastly, the greywater footprint indicates the volume of freshwater needed to dilute the pollutants produced, based on current ambient water quality standards (Mekonnen and Hoekstra, 2010).

The WF concept is closely related to the idea of virtual water. Virtual water is the amount required to produce a specific commodity or service. This concept was introduced by Allan in the early 1990s (Allan, 1993, 1994) while studying the feasibility of importing virtual water as a solution to water scarcity issues in the Middle East. Allan proposed that virtual water imports— which accompany food imports— could help alleviate the pressure on limited domestic water resources.

While many countries trade water-intensive goods, few governments consider the alternative of conserving water by importing these products, thereby leveraging their water abundance for additional benefits (Hoekstra and Mekonnen, 2012). Evaluating the sustainability of the water footprint throughout the supply chain of products and sharing pertinent information will become increasingly crucial for investors (Hoekstra, 2013).

Hoekstra and Chapagain (2007) calculated the WF for each nation in the world from 1997 to 2001. Their results indicated that the USA has an average WF of 2,480 $m^3$ per capita per year, while China has an average of 700 $m^3$ per capita per year. The global average WF is 1,240 $m^3$ per capita per year. The four major factors that directly influence a country's water footprint are: the volume of consumption (which is related to gross national income), consumption patterns (for example, high versus low meat consumption), climate (which affects growth conditions), and agricultural practices (including water use efficiency). In addition, Mekonnen and Hoekstra (2011a) reported that the global water footprint for crop production between 1996 and 2005 was 7,404 billion cubic meters per year, comprising 78% green water, 12% blue water, and 10% gray water. Notably, wheat had the largest total water footprint at 1,087 billion cubic meters per year, followed closely by rice at 992 billion cubic meters per year, and maize at 770 billion cubic meters per year. Wheat and rice together accounted for 45% of the global blue water footprint, making them significant contributors.

Alamri and Reed (2019) estimated the virtual water trade for 20 crops in Saudi Arabia from 2000 to 2016. Their findings indicated that the annual virtual water trade was 12.6 billion $m^3$/year. Saudi Arabia had net virtual water imports, with the most significant imports occurring for cereals, alfalfa, and vegetables. Additionally, there was a virtual water export for fruits. This virtual water trade helped reduce pressure on the country’s water resources by 54%.

Cao et al. (2018) reported that water scarcity is the main limiting factor for crop production in arid and semi-arid regions. In their study, they calculated the crop production water footprint in Shandong Province, in China, from 1996 to 2015 and analyzed the factors influencing it. The results showed that the annual CPWF was 173.1 billion cubic meters (G $m^3$), with blue, green, and grey water footprints accounting for 12.7%, 64.6%, and 22.7%, respectively. Additionally, the water footprints of grain and fruit crops made up more than 80% of the total water footprint. In the same direction, ElFetyany et al. (2021) highlighted that the water footprint is a metric that quantifies both direct and indirect water use throughout a product's life cycle. This indicator measures how much freshwater a product consumes, enabling the assessment of water efficiency by determining the optimal amount of water needed to achieve the highest return for one cubic meter of water. Furthermore, the water footprint can enhance sustainable agricultural practices and inform international trade structures. It emphasizes the necessity of integrating water resource management policies with agricultural and trade strategies to create a comprehensive national water accounting system.

Mehla (2022) highlighted that assessing the water footprint allows us to identify the impacts and limitations of our current systems. By recognizing vulnerabilities across different regions and timeframes, we can prepare suitable actions to enhance water productivity and promote sustainable water use. Technology and effective management practices are crucial in minimizing unnecessary water consumption.

However, climate change, water scarcity, and increasing demands from various sectors complicate this effort. Therefore, it has become essential to promote efficient and sustainable water use through improved planning (Hoekstra, 2017). There is a pressing need to develop better water management policies to satisfy current and future demands, ensuring food security while addressing domestic and industrial needs.

The research aims to calculate the water footprint of Egyptian crops both inside and outside the Nile Valley and Delta. It will also analyze Egypt's per capita water footprint associated with these crops.

Furthermore, the study will evaluate the percentage of dependence on external water sources and assess the national water self-sufficiency in agriculture. Additionally, it will estimate the volume of virtual water exported and imported for crops, highlighting the significance of international water trade in enhancing water and food security in Egypt.

## 2. Materials and Methods

The Arab Republic of Egypt is situated in northeastern Africa, extending into Asia, where the Sinai Peninsula is located in the southwestern part of the continent of Asia. Egypt primarily experiences a dry tropical climate, except for its northern regions, which fall within the temperate greenhouse zone. This northern area is characterized by a Mediterranean climate, featuring hot and dry summers and mild winters, accompanied by light rainfall that increases slightly along the north coast. In addition, Egypt is characterized by diverse climatic regions that differ from one area to another, offering opportunities to enhance both the quantity and quality of its agricultural production. The country can be divided into three main climatic zones: the Mediterranean coast, particularly near Alexandria and Port Said; the inland areas, which include the Nile Valley and the Nile Delta; and the western and eastern deserts. (https://www.worlddata.info/africa/egypt/climate.php).

Additionally, the Sustainable Agricultural Development Strategy 2030 (SADS, 2009) categorizes Egypt into five geographical regions based on agricultural considerations. These regions are the East Delta, West Delta, Middle Delta, Middle Egypt, and Upper Egypt. This classification encompasses all old and new agricultural lands inside and outside the Nile Valley and Delta.

### 2.1. Study areas:

This study focused on 14 agricultural climatic areas representing the old and new lands inside and outside the Nile Valley and the Delta. Table 1 shows the study areas and their coordinates.

### 2.2 Data collection

2.2.1. Agricultural meteorological data were obtained from the NASA website (POWER | Data Access Viewer (nasa.gov)) according to the coordinates of each study area, from 2019 to 2022. Figures 1 and 2 illustrate the trends in reference evapotranspiration under the conditions of the studied areas, along with the monthly mean during the study period

2.2.2. Data on crop productivity for the winter, summer, and Nili seasons were obtained from the Economic Affairs Sector of the Ministry of Agriculture and Land Reclamation (EAS-MALR, Volumes 2019 to 2023).

2.2.3. The data for the population census was obtained from CAPMAS (2021-2023).

2.2.4. The data on imported and exported crops and total crop production for the crops under study were obtained from the Food Balance in the Arab Republic of Egypt (EAS-MALR) and CAPMAS.

### 2.3. Selected crops

In Egypt, there are two main seasons for cultivating field and vegetable crops: the winter season (October through April), and the summer season (May through September). Additionally, there is sometimes a third season known as the Nili season (July through August), along with perennial crops that grow year-round. For this study, 59 crops were selected, representing all seasons except for the perennial crops. A list of the chosen crops can be found in Table 2.

### 2.4. Methodology

The present study utilized the CropWat 8.0 model (Allen et al., 1998) to calculate the green and blue water footprints. The calculations were performed on 59 crops, representing various planting seasons, including winter, summer, and Nili, for both field crops and vegetables.

Crop water requirements have been calculated for each crop and each area under study. The crop water requirement refers to the amount of water needed for evapotranspiration under ideal growth conditions, which is measured from planting to harvest. "Ideal conditions" means that sufficient soil moisture is maintained through rainfall and/or irrigation, ensuring that neither plant growth nor crop yield is limited (Hoekstra et al., 2011). The crop water requirement is determined by multiplying the reference crop evapotranspiration (ETo) by the crop coefficient (Kc): $CWR = Kc \times ETo$.

It is assumed that crop water requirements are fully met, so crop evapotranspiration (ETc) will equal the crop water requirement: $ETc = CWR$. Values of Kc for various crops throughout their growing season were obtained from FAO No. 56, with some adjustments based on actual field trials conducted in Egypt.

The irrigation requirement (IR) is calculated as the difference between the crop water requirement and effective precipitation. If effective rainfall exceeds the crop water requirement, the irrigation requirement is zero: $IR = \max(0, CWR - Peff)$. It is assumed that the irrigation requirements are fully satisfied.

National water footprints can be evaluated in two ways. The bottom-up approach involves calculating the sum of all goods and services consumed multiplied by their respective virtual water content, which varies depending on the location and conditions of production. In contrast, the top-down approach calculates a nation's water footprint by adding the total use of domestic water resources to the virtual water flows entering the country and subtracting the virtual water flows leaving the country (Chapagain and Hoekstra, 2004).

In this study, we employ two approaches: the bottom-up method to calculate the water footprint of crops, and a second method to assess the per capita water footprint along with the total virtual water linked to the imports and exports of the crops being studied.

**Calculation of the water footprint associated with national consumption of crops:**

The water footprint of a country (in cubic meters per year) refers to the total volume of water used, either directly or indirectly, to produce the goods and services consumed by its inhabitants (Chapagain and Hoekstra, 2004; Hoekstra et al., 2011). A national water footprint consists of two components: the internal water footprint and the external water footprint. The internal water footprint is defined as the use of domestic water resources to produce goods and services consumed within the country. It represents the total volume of water drawn from domestic resources for the national economy, minus the volume of virtual water exported to other countries, which relates to the export of domestically produced products. This study focuses solely on the agricultural sector, excluding the industrial and domestic sectors.

**Calculation Procedures**

**Step 1: Calculate the national consumption water footprint ($WF_{cons,nat}$):**

The water footprint was analyzed using the methodology outlined by Hoekstra et al. (2011). The total water footprint of growing crops ($WF_{proc}$) is the sum of the green, blue, and grey components.

$$WF_{proc} = WF_{proc,green} + WF_{proc,blue} + WF_{proc,grey} \quad (1)$$

This study did not calculate the gray water footprint due to a lack of necessary data. The green and blue water footprints ($WF_g$ and $WF_b$) are calculated as follows:

$$WF_g = \frac{CWU_{green}}{Y} \quad (2)$$

$$WF_b = \frac{CWU_{blue}}{Y} \quad (3)$$

$$WF_{cons,nat} = TWF_{per\ crop} + VW_i - VW_e \quad (4)$$

The terms $CWU_{green}$ and $CWU_{blue}$ represent the crop water use for green and blue water sources, respectively. The symbol "Y" indicates crop yield. The term '$WF_{cons,nat}$' refers to the national water footprint for the crops being studied. '$TWF_{per\ crop}$' denotes each crop's internal national water footprint, which is measured in cubic meters per ton ($m^3$/ton). This value is then multiplied by the total production to calculate the overall water footprint for that crop. '$VW_i$' indicates the virtual water imported for each crop, while '$VW_e$' represents the virtual water exported.

**Step 2: Water footprint per capita per crop ($WF_{pc}$, $m^3$/ capita/ season):**

Egypt's per capita water footprint is determined by $WF_{cons,nat,}$ divided by the number of inhabitants

$$WF_{pc} = \frac{WF_{cons,nat}}{\text{Total population}} \quad (5)$$

**Step 3: National water import dependency versus water self-sufficiency**

According to Mekonnen and Hoekstra (2011b), virtual water dependency (WD, %) for a nation is defined as the ratio of its external water footprint ($VW_{ext}$) to the total water footprint associated with national consumption ($WF_{cons,nat}$).

$$WD = \frac{VW_{ext}}{WF_{cons,nat}} \times 100 \quad (6)$$

**Step 4: National Water Self-Sufficiency (WSS, %):** Water self-sufficiency is defined as the ratio of the internal water footprint ($WF_{con,nal,int}$) to the national water footprint ($WF_{cons,nat}$).

$$WSS = \frac{WF_{con,nal,int}}{WF_{cons,nat}} \times 100 \quad (7)$$

**Step 5: National water savings ($S_n$) related to international trade of agricultural products:**

National water savings ($S_n$) associated with international trade in agricultural products are determined by calculating the difference between a country's net import volume of a specific commodity and its export volume. It is important to note that these calculated savings can be negative, which indicates a national net loss of water rather than an actual saving (Mekonnen and Hoekstra, 2011b).

$$S_n = VW_i - VW_e \quad (8)$$

Table 1: Locations of study areas along with their latitude and longitude coordinates

| | Governorate/ area | Latitude | Longitude |
|---|---|---|---|
| Inside the Nile Valley and Delta | Lower Egypt | | |
| | Behyra | 31.02 | 30.28 |
| | Kafr El-Sheikh | 31.07 | 30.57 |
| | Dakhalia | 31.03 | 31.23 |
| | Sharkia | 30.24 | 31.25 |
| | Monofya | 30.36 | 31.01 |
| | Middle Egypt | | |
| | Bani Sweif | 29.04 | 31.06 |
| | Fayoum | 29.18 | 30.51 |
| | Minya | 28.05 | 30.44 |
| | Upper Egypt | | |
| | Asyout | 27.03 | 31.01 |
| | Sohag | 26.34 | 31.42 |
| | Qena | 26.1 | 32.43 |
| Outside the Nile Valley and Delta | El-Wady El-Gadeed | 24.55 | 27.17 |
| | Matrouh | 31.2 | 27.13 |
| | Nubaria | 30.39 | 30.42 |

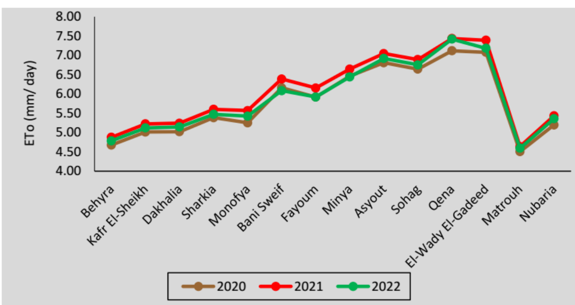


Figure 1: Average annual reference evapotranspiration (ETo) in the studied governorates

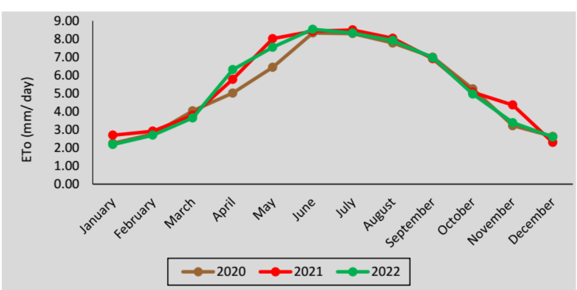


Figure 2: Average monthly reference evapotranspiration (ETo) in Egypt from 2020 to 2022.

## 3. Results

### 3.1. Water footprint for Egyptian crops

The results presented in Figure 3 show the average green and blue water footprints ($WF_g$ and $WF_b$) of winter field crops in Egypt, based on data collected over three years from 2019/2020 to 2021/2022. The $WF_g$ varied significantly, ranging from 15.5 m³/ton for onions to 259.5 m³/ton for chickpeas. In contrast, the average $WF_b$ during the same period ranged from 102.5 m³/ton for onions to 838.7 m³/ton for dry faba beans. Overall, the average $WF_g$ and $WF_b$ for all the winter field crops studied were 104.0 and 403.6 m³/ton, respectively.

Table 2: Selected crops for the study across different seasons (59 crops)

| Winter field crops (W) | Summer field crops (S) | Nili field and vegetable crops (N) |
|---|---|---|
| Barley | Cotton | Beans (g) |
| Chickpeas | Ground nut | Beans (d) |
| Faba bean (g) | Maize | Cabbage |
| Faba bean (d) | Onion | Cantaloupe |
| Flax | Soybean | Carrot |
| Garlic | Sunflower | Cucumber |
| Onion | Sugarcane | Eggplant |
| Sugar beet | **Summer vegetables (S)** | Maize |
| Wheat | Beans (g) | Pepper |
| **Winter vegetables (W)** | Beans (d) | Potato |
| Beans (g) | Cabbage | Squash |
| Beans (d) | Cantaloupe | Sunflower |
| Cabbage | Carrot | Tomato |
| Cantaloupe | Cucumber | |
| Carrot | Eggplant | |
| Cucumber | Okra | |
| Eggplant | Pepper | |
| Lettuce | Potato | |
| Peas (g) | Squash | |
| Peas (d) | Taro | |
| Pepper | Tomato | |
| Potato | Watermelon | |
| Squash | | |
| Strawberry | | |
| Tomato | | |
| Watermelon | | |

Note: "W" signifies the winter season; "S" represents the summer season; "N" indicates the Nili season; "d" stands for dry crops; "g" denotes green crops.

In terms of the water footprint for winter vegetable crops, the results presented in Figure 4 indicate that the $WF_g$ ranged from 7.4 to 192.1 m³/ton, while the $WF_b$ ranged from 62.6 to 1347.2 m³/ton. The overall average water footprint for the winter vegetable group was 33.9 m³/ton for the $WF_g$ and 241.1 m³/ton for the $WF_b$.

Figure 5 illustrates the water footprint values for summer field crops. The $WF_g$ varied from 0.3 to 32.3 m³/ton, while the $WF_b$ ranged from 156.5 to 2350.2 m³/ton. The WF for the summer field crop group was 5.9 m³/ton for the $WF_g$ and 1571.8 m³/ton for the $WF_b$.

The results for the summer vegetable group showed that the $WF_g$ ranged from 2.1 to 150.1 m³/ton, while the $WF_b$ varied between 80.5 and 1567.3 m³/ton (as seen in Figure 6). The overall average for the $WF_g$ and $WF_b$ were 25.3 and 359.7 m³/ton, respectively.

Concerning the Nili crop group under study, results as indicated in Figure 7 showed that the $WF_g$ ranged from 0.1 to 113.7 m³/ton, whereas the $WF_b$ ranged from 186.7 to 1822.3 m³/ton. The overall averages for this group were recorded at 12.1 m³/ton for the $WF_g$ and 550.7 m³/ton for the $WF_b$.

Effective rainfall plays a minor role in the total water footprint, with contribution percentages of 26%, 14%, 0.4%, 7%, and 2% for winter fields, winter vegetables, summer fields, summer vegetables, and Nili crop groups, respectively (see Figure 8).

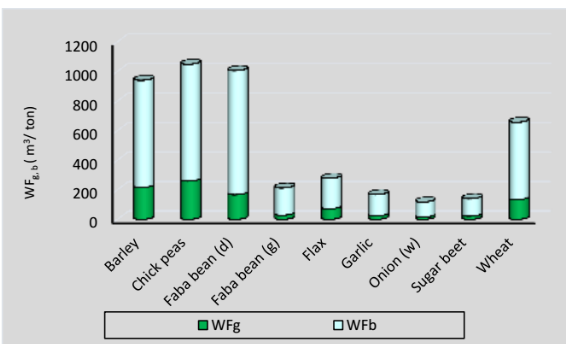


Figure 3: Green and blue water footprint ($WF_{g,\,b}$) of winter field crops over three seasons (2019/2020-2021/2022)

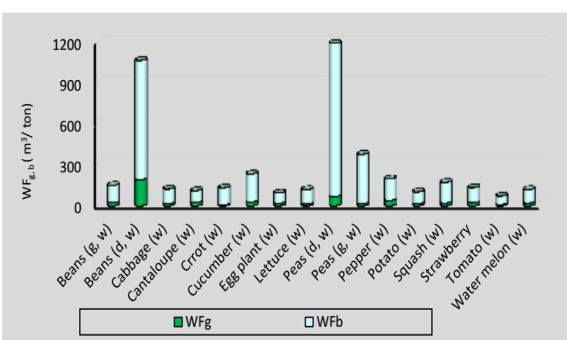


Figure 4: Green and blue water footprint ($WF_{g,\,b}$) of winter vegetables over three seasons (2019/2020-2021/2022)

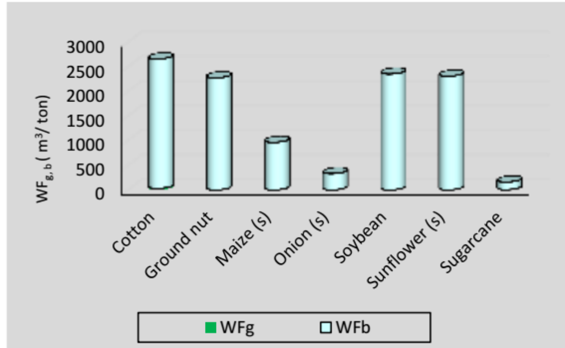


Figure 5: Green and blue water footprint ($WF_{g,\,b}$) of summer field crops over three seasons (2020-2022)

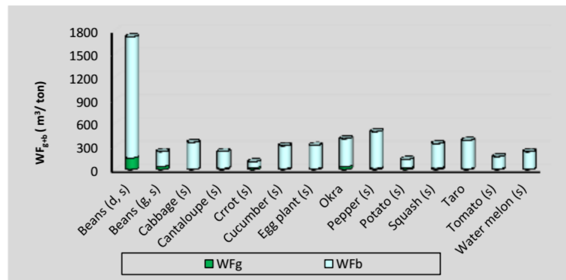


Figure 6: Green and blue water footprint ($WF_{g,\,b}$) of summer vegetables over three seasons (2020-2022)

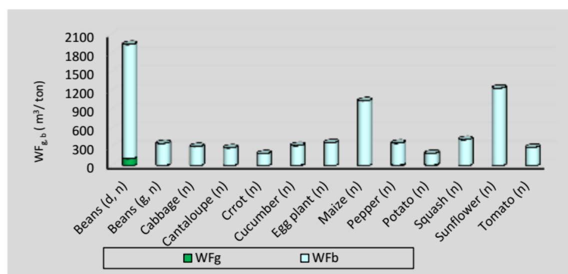


Figure 7: Green and blue water footprint ($WF_{g,\,b}$) of Nili crops over three seasons (2020-2022)

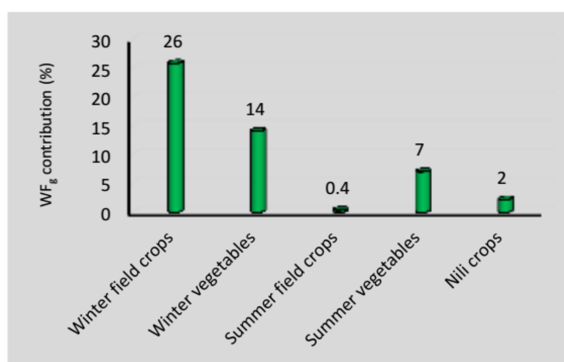


Figure 8: Contribution of the green water footprint to the total water footprint of Egyptian crops

### 3.2. Average total water footprint ($WF_{g+b}$) inside and outside the Nile Valley and Delta over three years of study

Figures 9-13 illustrate the average total water footprint of different crop groups studied inside and outside the Nile Valley and the Delta. The results indicate the following average total water footprints: for winter field crops, 563 m³/ton inside the Nile Valley and 489 m³/ton outside; for winter vegetables, 322 m³/ton inside and 279 m³/ton outside; for summer field crops, 1,673 m³/ton inside and 1,481 m³/ton outside; for summer vegetables, 420 m³/ton inside and 366 m³/ton outside; and for Nili crops, 547 m³/ton inside and 559 m³/ton outside. These data show that crop groups grown outside the Nile Valley and the Delta generally have a lower water footprint than those grown inside the Nile Valley and the Delta. The only exception is the Nili crop group, which performs slightly better in terms of water footprint inside the Nile Valley and the Delta.

Based on the previous results, it can be concluded that the average total green and blue water footprint ($WF_{g+b}$) for the crops during the study period was recorded at 508, 275, 1,578, 385, and 563 m³/ton for the following crop groups: winter fields, winter vegetables, summer fields, summer vegetables, and Nili, respectively (Table 3). The overall average water footprint of Egyptian crops was 662 m³/ton. These findings are consistent with the study by El-Marsafawy and Mohamed (2021), which reported an average water footprint of Egyptian crops of 680 m³/ton.

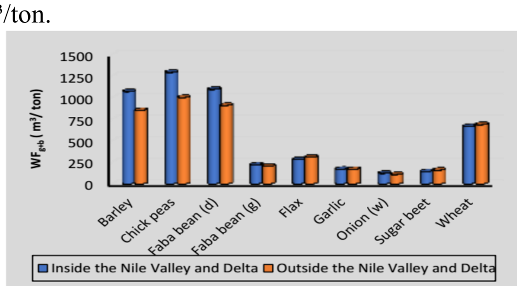


Figure 9: Average total water footprint of winter field crops inside and outside the Nile Valley and Delta

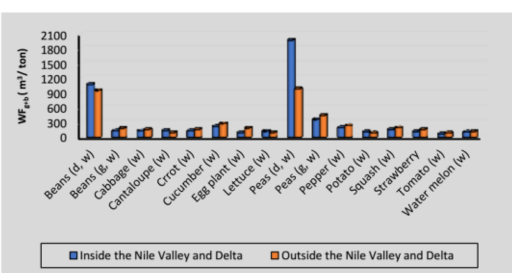


Figure 10: Average total water footprint of winter vegetables inside and outside the Nile Valley and Delta

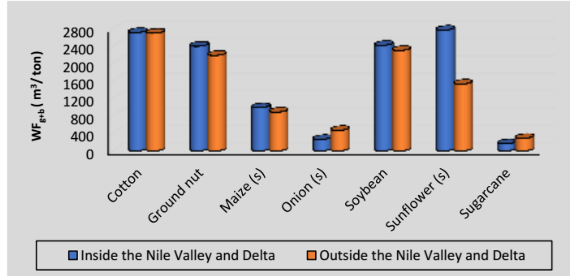


Figure 11: Average total water footprint of summer field crops inside and outside the Nile Valley and Delta

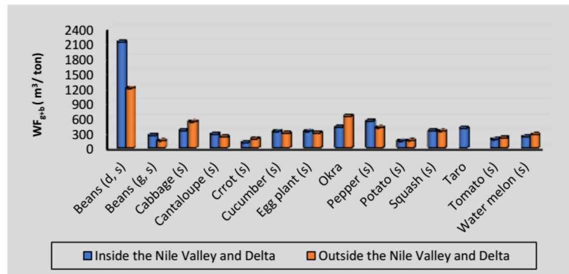


Figure 12: Average total water footprint of summer vegetables inside and outside the Nile Valley and Delta

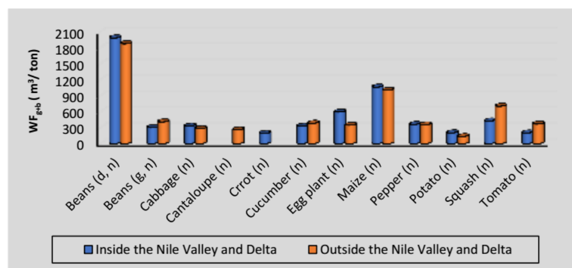


Figure 13: Average total water footprint of Nili crops inside and outside the Nile Valley and Delta.

Note: In the graphs, the absence of any crop columns indicates that the crops are not planted in this area or during this agricultural season.

Table 3: Average total water footprints ($WF_{g+b}$) for the crop groups under study

| Crop groups | 1st season | 2nd season | 3rd season | Average 3 seasons |
|---|---|---|---|---|
| Winter field crops | 512 | 535 | 477 | 508 |
| Winter vegetables | 287 | 268 | 270 | 275 |
| Summer field crops | 1551 | 1590 | 1594 | 1578 |
| Summer vegetables | 365 | 408 | 381 | 385 |
| Nili crops | 527 | 558 | 603 | 563 |
| Overall average | 648 | 672 | 665 | 662 |

### 3.3. Water footprint per capita ($WF_{pc}$) for the crops studied

Due to the unavailability of essential data, such as export and import figures, the remaining studies will focus on only 25 crops. Table 4 illustrates the average $WF_{pc}$ for the crops under study. The findings indicate that the average $WF_{pc}$ for the winter field crop group varied widely, ranging from 0.7 $m^3$/capita for garlic to about 130 $m^3$ for wheat. Summer and Nili field crop groups showed a similar range, with a $WF_{pc}$ of 1.4 $m^3$ for sunflower and 163 $m^3$ for maize. Regarding vegetables, the $WF_{pc}$ ranged from 0.2 $m^3$ for carrots to 8.5 $m^3$ for potatoes and 10.7 $m^3$ for tomatoes.

### 3.4. Dependence on imported virtual water versus water self-sufficiency (WD, %)

Table 5 presents the percentage of dependence on external virtual water versus the water self-sufficiency of the crops under study. The results indicate that, for the winter field crop group, the average dependence rate on external virtual water varied from zero for sugar beet to 85% for dry faba beans. Summer and Nili field groups ranged from 0.01 % for sugarcane to 99% for soybeans. In contrast, vegetable crops showed a very low dependence on external water, suggesting a high level of national water self-sufficiency for most of these crops.

Table 4: Water footprint per capita ($WF_{cp}$) in Egypt for selected crops during three seasons

| Crops | $WF_{pc}$, $m^3$ | | | Average 3 seasons ($WF_{pc}$, $m^3$) |
|---|---|---|---|---|
| | 1st season | 2nd season | 3rd season | |
| Field crops (W) | | | | |
| Barley | 1.4 | 1.7 | 1.2 | 1.4 |
| Faba bean (d) | 7.5 | 8.1 | 5.7 | 7.1 |
| Garlic | 0.6 | 0.7 | 0.8 | 0.7 |
| Onion | 4.8 | 5.7 | 7.9 | 6.2 |
| Sugar beet | 14.7 | 19.9 | 17.0 | 17.2 |
| Wheat | 143.4 | 133.1 | 113.3 | 129.9 |
| Field crops (S, N) | | | | |
| Cotton (S) | 7.1 | 8.7 | 12.8 | 9.6 |
| Ground nut (S) | 3.5 | 3.1 | 4.1 | 3.6 |
| Maize (S, N) | 166.3 | 158.0 | 165.7 | 163.3 |
| Soybean (S) | 111.3 | 106.9 | 94.0 | 104.0 |
| Sunflower (S, N) | 1.7 | 1.4 | 1.0 | 1.4 |
| Sugarcane (S) | 24.7 | 26.1 | 25.4 | 25.4 |
| Vegetables (W, S, N) | | | | |
| Beans (g) | 0.4 | 0.3 | 0.2 | 0.3 |
| Cabbage | 0.0 | 1.2 | 1.3 | 0.8 |
| Carrot | 0.0 | 0.3 | 0.2 | 0.2 |
| Cucumber | 1.6 | 1.6 | 2.5 | 1.9 |
| Eggplant | 0.0 | 4.5 | 4.9 | 3.1 |
| Peas (g) | 0.6 | 0.8 | 0.5 | 0.6 |
| Pepper | 2.9 | 3.0 | 4.1 | 3.4 |
| Potato | 9.1 | 8.1 | 8.4 | 8.5 |
| Squash | 0.0 | 1.2 | 1.7 | 0.9 |
| Strawberry | 0.3 | 0.4 | 0.4 | 0.4 |
| Taro | 0.4 | 0.6 | 0.7 | 0.6 |
| Tomato | 10.9 | 10.2 | 11.0 | 10.7 |
| Watermelon | 1.8 | 1.7 | 1.7 | 1.7 |

### 3.5. National water self-sufficiency (WSS, %)

The results in Table 6 indicate the percentage of water self-sufficiency over the three years of study. The findings reveal that the average national water self-sufficiency for the winter field crop group varied, with dry faba beans at 14.8% and sugar beet at 100%. In the case of the summer and Nili field crops group, the range was from 1% for soybean to 99.99% for sugarcane. For the vegetable crops group, the percentage is around 100%.

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Table 5: Percentage of dependence on external virtual water (WD%) versus water self-sufficiency

| Crops | WD (%) | | | Average |
|---|---|---|---|---|
| | 1st seaso | 2nd Seaso | 3rd Season | (WD, %) |
| Field crops (W) | | | | |
| Barley | 5.5 | 7.2 | 0.0 | 4.2 |
| Faba bean | 85.5 | 83.2 | 86.8 | 85.2 |
| Garlic | 2.9 | 1.9 | 4.6 | 3.1 |
| Onion | 0.2 | 0.0 | 0.1 | 0.1 |
| Sugar beet | 0.0 | 0.0 | 0.0 | 0.0 |
| Wheat | 59.9 | 54.3 | 49.6 | 54.6 |
| Field crops (S, N) | | | | |
| Cotton (S) | 41.6 | 28.6 | 25.5 | 31.9 |
| Ground | 2.7 | 2.1 | 0.5 | 1.8 |
| Maize (S, | 55.3 | 54.1 | 51.5 | 53.6 |
| Soybean | 99.2 | 99.2 | 98.5 | 99.0 |
| Sunflower | 85.4 | 81.7 | 69.8 | 79.0 |
| Sugarcane | 0.02 | 0.01 | 0.01 | 0.01 |
| Vegetables (W, S, N) | | | | |
| Beans (g) | 0.0 | 0.0 | 0.0 | 0.0 |
| Cabbage | | 0.0 | 0.0 | 0.0 |
| Carrot | | 0.0 | 0.0 | 0.0 |
| Cucumber | 0.5 | 0.3 | 0.1 | 0.3 |
| Eggplant | | 0.0 | 0.0 | 0.0 |
| Peas (g) | 4.6 | 1.4 | 3.3 | 3.1 |
| Pepper | 0.0 | 0.0 | 0.0 | 0.0 |
| Potato | 1.9 | 2.3 | 2.4 | 2.2 |
| Squash | | 0.00 | 0.00 | 0.0 |
| Strawberry | 0.0 | 0.0 | 0.0 | 0.0 |
| Taro | 0.0 | 0.0 | 0.0 | 0.0 |
| Tomato | 0.3 | 0.2 | 0.1 | 0.2 |
| Watermelo | 0.0 | 0.0 | 0.0 | 0.0 |

Table 6: National water self-sufficiency (WSS, %) for Egyptian crops across three growing seasons

| Crops | WSS (%) | | | Averag |
|---|---|---|---|---|
| | 1st Season | 2nd Season | 3rd Season | WSS (%) |
| Field crops (W) | | | | |
| Barley | 94.5 | 92.8 | 100.0 | 95.8 |
| Faba bean | 14.5 | 16.8 | 13.2 | 14.8 |
| Garlic | 97.1 | 98.1 | 95.4 | 96.9 |
| Onion | 99.8 | 100.0 | 99.9 | 99.9 |
| Sugar beet | 100.0 | 100.0 | 100.0 | 100.0 |
| Wheat | 40.1 | 45.7 | 50.4 | 45.4 |
| Field crops (S, N) | | | | |
| Cotton (S) | 58.4 | 71.4 | 74.5 | 68.1 |
| Ground nut | 97.3 | 97.9 | 99.5 | 98.2 |
| Maize (S, | 44.7 | 45.9 | 48.5 | 46.4 |
| Soybean | 0.8 | 0.8 | 1.5 | 1.0 |
| Sunflower | 14.6 | 18.3 | 30.2 | 21.0 |
| Sugarcane | 99.98 | 99.99 | 99.99 | 99.99 |
| Vegetables (W, S, N) | | | | |
| Beans (g) | 100.0 | 100.0 | 100.0 | 100 |
| Cabbage | | 100.0 | 100.0 | 100 |
| Carrot | | 100.0 | 100.0 | 100 |
| Cucumber | 99.5 | 99.7 | 99.9 | 99.7 |
| Eggplant | | 100.0 | 100.0 | 100 |
| Peas (g) | 95.4 | 98.6 | 96.7 | 96.9 |
| Pepper | 100.0 | 100.0 | 100.0 | 100 |
| Potato | 98.1 | 97.7 | 97.6 | 97.8 |
| Squash | | 100.0 | 100.0 | 100 |
| Strawberry | 100.0 | 100.0 | 100.0 | 100 |
| Taro | 100.0 | 100.0 | 100.0 | 100 |
| Tomato | 99.7 | 99.8 | 99.9 | 99.8 |
| Watermelo | 100.0 | 100.0 | 100.0 | 100 |

### 3.6. National water savings ($S_n$) from virtual water trade in crops.

Table 7 provides an overview of the net international trade of virtual water related to the crops under study, highlighting the increase and decrease in Egypt's water resources. It is important to note that a negative value in this table indicates the export of virtual water from Egypt, while non-negative values represent Egypt's imports of virtual water through agricultural products. The analysis revealed the following average values over the three years studied:

- For the winter field crops group, the values ranged from -151 million m³ (onions) to 7 billion m³ (wheat).
- In the summer and Nili field crops group, values ranged from -141 million m³ (ground nuts) to 10.5 billion m³ (soybeans).
- Values ranged from approximately -103 million m³ (potatoes) to -911 thousand m³ (squash) for the vegetable crops group.

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Table 7: National water savings in Egypt's agricultural sector resulting from crop trading

| Crops | Virtual Water Imported | Virtual Water Exported | Water saving ($S_n$) ($VW_i$ - $VW_e$) |
|---|---|---|---|
| | Average 3 seasons | | |
| Field crops (W) | | | |
| Barley | 10,285,500 | 7,898,667 | 2,386,833 |
| Faba bean (d) | 614,733,000 | 34,129,000 | 580,604,000 |
| Garlic | 2,265,333 | 6,359,667 | -4,094,333 |
| Onion | 638,000 | 151,686,333 | -151,048,333 |
| Sugar beet | 0 | 0 | 0 |
| Wheat | 7,281,533,333 | 285,128,333 | 6,996,405,000 |
| Field crops (S, N) | | | |
| Cotton (S) | 297,683,133 | 171,762,589 | 125,920,544 |
| Ground nut (S) | 6,108,333 | 147,155,667 | -141,047,333 |
| Maize (S, N) | 8,937,073,667 | 8,933,000 | 8,928,140,667 |
| Soybean (S) | 10,508,510,000 | 0 | 10,508,510,000 |
| Sunflower (S, N) | 111,019,000 | 12,060,000 | 98,959,000 |
| Sugarcane (S) | 329,000 | 276,000 | 53,000 |
| Vegetables (W, S, N) | | | |
| Beans (g) | 0 | 10,624,222 | -10,624,222 |
| Cabbage | 0 | 1,062,000 | -1,062,000 |
| Carrot | 0 | 3,210,667 | -3,210,667 |
| Cucumber | 481,778 | 4,922,778 | -4,441,000 |
| Eggplant | 0 | 1,394,667 | -1,394,667 |
| Peas (g) | 1,749,333 | 5,830,000 | -4,080,667 |
| Pepper | 0 | 2,320,667 | -2,320,667 |
| Potato | 18,966,000 | 121,829,000 | -102,863,000 |
| Squash | 0 | 910,500 | -910,500 |
| Strawberry | 0 | 42,912,000 | -42,912,000 |
| Taro | 0 | 1,403,667 | -1,403,667 |
| Tomato | 2,351,889 | 56,744,778 | -54,392,889 |
| Watermelon | 0 | 1,746,833 | -1,746,833 |

## 4. Discussion

Egypt's agricultural sector faces several significant challenges, including rapid population growth, limited water resources, and its classification as a dry region with less than 200 mm of annual rainfall. These factors have contributed to a gap between agricultural production and consumption. Table 8 presents the self-sufficiency rates of major crops in Egypt from 2020 to 2022. The data shows that the self-sufficiency ratios for several important field crops, including wheat, maize, soybeans, dry faba beans, and sunflower seeds, have declined by more than 50%.

Conversely, the international trade in virtual water, represented through the exchange of crops, has improved the circumstances for countries struggling with self-sufficiency. Table 9 shows the average net import and export of virtual water during the study period. Egypt's total virtual water exports reached approximately 231 million $m^3$, while the virtual water imports amounted to 26.9 billion $m^3$. It is important to note that these figures relate only to the 25 crops included in the study. Therefore, it can be concluded that Egypt has effectively added about 27 billion $m^3$ of virtual water to its overall water resources. This addition has played a crucial role in maintaining water security and enhancing food security in the country.

Although Egypt imports large quantities of virtual water in the form of various crops, it stands out regarding the water footprint of individual crops, measured in cubic meters per ton. In this research, we utilized total global green and blue water footprint data from a study by Mekonnen and Hoekstra conducted in (2011a). Our objective was to compare this data with the water footprints of the crops we investigated to determine whether land and water resources are managed effectively.

Table 8: Self-sufficiency in Egypt for some crops during the period from 2020 to 2022.

| Crop | Self-sufficiency (%) | | | |
|---|---|---|---|---|
| | 2020 | 2021 | 2022 | Average |
| **Field crops** | | | | |
| Wheat | 42.4 | 46.6 | 51.5 | 47 |
| maize | 44.8 | 46.0 | 48.5 | 46 |
| Soybean | 0.8 | 0.8 | 1.5 | 1 |
| Faba bean | 17.3 | 21.1 | 20.9 | 20 |
| Sunflower | 19.5 | 29.6 | 41.5 | 30 |
| Ground nut | 133.6 | 151.4 | 133.3 | 139 |
| Onion | 123.4 | 120.6 | 126.8 | 124 |
| **Vegetables** | | | | |
| Beans | 116.0 | 134.6 | 162.8 | 138 |
| Cucumber | 102.1 | 102.0 | 107.7 | 104 |
| Potato | 105.1 | 110.6 | 113.7 | 110 |
| Strawberry | 194.7 | 221.6 | 223.7 | 213 |
| Tomato | 104.7 | 105.0 | 105.2 | 105 |
| Watermelon | 101.0 | 100.9 | 101.0 | 101 |

Source: EAS-MALR, Volumes 2020 to 2022

Table 9: Total national water savings from virtual international water trade for various studied crops (three-year average).

| Crop | $S_n$ ($m^3$) |
|---|---|
| Field crops | 26,944,789,044 |
| Vegetable crops | -231,362,778 |
| Total | 26,713,426,266 |

Table 10 presents the average water footprints of the crops studied alongside their global counterparts. The results indicate that the water footprints of Egyptian crops are generally more efficient than the global averages for most crops examined. This discrepancy can be attributed to effective land and water management practices in Egypt, as well as various environmental factors that influence production. These factors include a favorable climate, high-yielding crop varieties, a short growing season, and soil fertility, among others. In contrast, the contribution of green water to Egypt's total water footprint is relatively small compared to the global average. This emphasizes the challenges Egypt faces, as the country relies heavily on blue water to fulfill its agricultural water requirements.

In this context, Agro Der (2012) noted that, on a global scale, the contributions of green, blue, and grey water were rated at 74%, 11%, and 15%, respectively. In the same direction, Chapagain et al. (2006) noted that Egypt's crop water requirements are relatively high compared to those of its trading partners. However, this is somewhat offset by the country's impressive wheat yields, which are more than twice the global average. Consequently, water productivity—measured as water use per unit of product—in wheat production in Egypt exceeds that of Canada, Turkey, and Australia. It's important to highlight that wheat production in Egypt relies on limited blue water resources, while partner countries utilize effective rainfall, known as green water. The net global water loss associated with wheat exports from Canada and other countries to Egypt arises because the volume of blue water resources required for domestic production in Egypt is smaller than the volume of green water used in Canada and similar countries. Blue and green water resources differ significantly in their applications and associated opportunity costs. To effectively analyze and interpret global water savings or losses, it is essential to separate these figures into blue and green water components

## 5. Conclusion

The current research focuses on analyzing the water footprint of Egyptian crops and calculating the per capita water footprint based on the crops studied. It also examines the volume of exports and imports of virtual water in the form of these crops, highlighting the significance of international trade in virtual water for maintaining water and food security in Egyptian agriculture.

The findings revealed that the average total water footprint for the crop groups studied ranged from 118 to 1,049 $m^3$/ton for winter field crops, from 73 to 1,188 $m^3$/ton for winter vegetables, from 165 to 2,656 $m^3$/ton for summer field crops, from 102 to 1,717 $m^3$/ton for summer vegetables, and from 192 to 1,936 $m^3$/ton for Nili crops.

The comparison of water footprints inside and outside the Nile Valley and the Delta showed that most crops outside the Nile Valley and the Delta had lower water footprints. Regarding average WF per capita during the study period, maize, wheat, and soybean had the highest values, reporting 163.3, 129.9, and 104.0 $m^3$/capita/year, respectively.

The national water self-sufficiency (WSS, %) for the studied crop groups showed that the minimum percentages recorded were 1% for soybeans, 14.8% for dry faba beans, 21.0% for sunflower, 46.4% for maize, and 45.4% for wheat, based on the average over the three years analyzed. Additionally, the amount of virtual water associated with the crops under study was approximately 231.4 million $m^3$ for exports and 26.9 billion $m^3$ for imports.

Table 10: Comparison of the green and blue water footprints ($WF_{g,b}$) of Egyptian crops versus their global counterparts.

| Crop | Egyptian WF ($m^3$/ton) (Average 3 years, $m^3$/ton) | | | Global WF ($m^3$/ton) (Average 10 years, $m^3$/ton) | | |
|---|---|---|---|---|---|---|
| | $WF_g$ | $WF_b$ | Total $WF_{g+b}$ | $WF_g$ | $WF_b$ | Total $WF_{g+b}$ |
| Barley | 216.3 | 724.5 | 941 | 1213 | 79 | 1292 |
| Chickpeas | 259.5 | 789.3 | 1049 | 2972 | 224 | 3196 |
| Faba bean (d) | 167.3 | 838.7 | 1006 | 1317 | 205 | 1522 |
| Garlic | 23.7 | 144.6 | 168 | 337 | 81 | 418 |
| Onion | 8.25 | 216.05 | 224 | 192 | 88 | 280 |
| Sugar beet | 21.8 | 118.7 | 141 | 82 | 26 | 108 |
| Wheat | 133.7 | 523.1 | 657 | 1277 | 342 | 1619 |
| | | | | | | |
| Cotton | 32.3 | 2624 | 2656 | 2282 | 1306 | 3588 |
| Ground nut | 0.7 | 2272.4 | 2273 | 2469 | 150 | 2619 |
| Maize | 0.8 | 999.5 | 1000 | 947 | 81 | 1028 |
| Soybeans | 0.8 | 2350.2 | 2351 | 2037 | 70 | 2107 |
| Sunflower | 0.85 | 1771.15 | 1772 | 3017 | 148 | 3165 |
| Sugarcane | 5.1 | 156.5 | 162 | 139 | 57 | 196 |
| | | | | | | |
| Beans (d) | 152.0 | 1552.5 | 1704 | 3945 | 125 | 4070 |
| Beans (g) | 23.1 | 224.0 | 247 | 320 | 54 | 374 |
| Cabbage | 6.4 | 254.1 | 261 | 181 | 26 | 207 |
| Carrot | 9.7 | 132.8 | 143 | 106 | 28 | 134 |
| Cucumber | 16.5 | 271.6 | 288 | 206 | 42 | 248 |
| Eggplant | 9.7 | 271.2 | 281 | 234 | 33 | 267 |
| Lettuce | 12.4 | 107.6 | 120 | 133 | 28 | 161 |
| Okra | 37.6 | 361.9 | 400 | 474 | 36 | 510 |
| Peas (d) | 68.5 | 1347.2 | 1416 | 1453 | 33 | 1486 |
| Peas (g) | 16.1 | 361.7 | 378 | 382 | 63 | 445 |
| Potato | 15.1 | 128.8 | 144 | 191 | 33 | 224 |
| Squash | 12.1 | 296.9 | 309 | 228 | 24 | 252 |
| Strawberry | 23 | 111.1 | 134 | 201 | 109 | 310 |
| Tomato | 6.1 | 172.0 | 178 | 108 | 63 | 171 |
| Watermelon | 11.6 | 199.1 | 211 | 147 | 25 | 172 |

**Author Contributions:**

Conceptualization, S.M.E.-M. and M.K.; Methodology, S.M.E.-M.; Data collection of crop productivity A.I.M., K.A.I.M.; Data collection of population growth, A.I.M., K.A.I.M.; Data collection of imported and exported crops, A.I.M., K.A.I.M., S.M.E.-M.; Software and validation, S.M.E.-M.; Writing-Original Draft Preparation, S.M.E.-M., and M.K.; Writing-Review & Editing, S.M.E.-M.

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