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Contributed Paper

# Water Footprint and Virtual Water Flow of Cassava Starch of Thailand

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## ABSTRACT

Cassava starch is a crucial agro-industry in Thailand. Cassava is extensively cultivated and processed into the final products in the country to be consumed and exported. Cassava cultivation and processing have a large impact on water resources, and also creates stress on water availability. Water footprint (WF) is the tool used for measuring the total amount of water consumed by an individual or an entire nation, and can be used to provide a clear overview mapping of water use during the time in which the product is consumed or traded. The aims of this study were to calculate the average WF of cassava starch production from crop to final product consumed under the WF concept methodology, and to assess the virtual water flow (VWF) of cassava starch trade in Thailand during the period of 2008-2013. The results showed that the average WF of crop cultivation was equal to 528 $m^3$/ton, consisting of green (187 $m^3$/ton), blue (251 $m^3$/ton) and grey (90 $m^3$/ton) components. The average WF of cassava starch was equal to 1,945 $m^3$/ton product, consisting of green (678 $m^3$/ton), blue (925 $m^3$/ton) and grey (342 $m^3$/ton), respectively. The amount of water required for crop cultivation is associated with the climatic and soil conditions. Moreover, adopting good farming practices and the most efficient irrigated water scheduling can reduce the amount of water needed per ton of crop cultivation. However, the water used in crop processing depends on processing operation and technology. The VWF of global exported cassava starch from Thailand was 3.68 billion $m^3$/year, almost 85% of which was distributed throughout Asia. The largest importers of cassava starch are China, Indonesia and Taiwan. The import of cassava starch might be able to support countries that have water scarcity problems. Instead of cultivating and processing it nationally, the import of cassava starch can help lessen the burden on domestic water resources.

**Keywords:** cassava, water footprint, crop cultivation, processing, trade, Thailand

## 1. INTRODUCTION

Cassava and its derivative are consumed in a variety of forms by humans. Cassava starch can further be processed into confectionery, sweeteners, glues, textiles, paper, etc. Moreover, cassava chips and pellets are used in animal feed and alcohol production [1]. According to FAOSTAT [2], it was reported that there is 20.1 million hectares used for global cassava cultivation and 254 million tons produced per year; it also stated that Thailand is the second-largest cassava producer in the world and the largest exporter of cassava starch. Cassava is cultivated in the Northern, Northeastern and Central Plains of Thailand. During the years 2008-2013, the average harvested area of cassava in Thailand as reported by the OAE [3-4] was around 1.26 million hectares, which produced 25.9 million tons of cassava per year. This was comprised of approximately 55% fresh cassava root transformed to starch and 65% of processed starch exported worldwide [5]. Nowadays, the cultivation of cassava consumes a large amount of both rainwater and irrigated water. To ensure high productivity, chemical fertilizers are applied to the crop area. The leaching of fertilizers from agricultural fields is one of the main causes of non-point source pollution of surface and sub-surface water bodies [6]. Moreover, cassava starch processing also requires a high volume of water consumption and the wastewater generated throughout the process has a detrimental effect on the environment. The water consumed for cassava starch production shows how much water is withdrawn from natural water resources to produce these products.

The water footprint (WF) concept was introduced by Hoekstra *et al.* [7], as an indicator of how to calculate the total volume of freshwater that is used to produce the products and services along the different steps of the supply chain. Chapagain and Hoekstra [8] described WF as an indicator of human appropriation of freshwater resources that incorporates both direct and indirect water use of a consumer or producer. Moreover, the water consumed in the production process of an agricultural or industrial product has been called the 'virtual water' contained in the product [9]. Hofwegen [10] explains that virtual form of water can be transported from one country to another country through the products and helps to support water-scarce countries. WF shows water consumption volume by source and the amount of water that is polluted by type of pollution [11]. WF consists of three components; green, blue and grey WFs. The green WF expresses the volume of rainwater that evaporates during crop growth; the blue WF refers to the volume of the surface and groundwater in a catchment area that evaporates due to crop growth; and the grey WF defines the volume of freshwater that is required to assimilate the load of pollutants based on natural background concentrations and existing ambient water quality standards [11]. This tool has evolved independently from the life cycle assessment (LCA) that focuses on the water-resource management perspective [12]. The aim of this study was to calculate the WF and virtual water flow (VWF) of cassava starch trade in Thailand during 2008-2013. This calculation was divided into three components; green, blue and grey WFs. The information acquired from this study will be useful for water resource planning and policy management in crop production in the future, including industrial processing and also for worldwide trade.

## 2. Materials and Methods

### 2.1 Scope of This Study

The scope of this study was divided into three categories; crop cultivation, production and commodity trade, as shown in Figure 1. The calculations of WF were conducted using the Water Footprint Assessment Manual introduced by Hoekstra *et al.* [11]. CROPWAT 8.0 software program was used to measure the green and blue components, developed by the Land and Water Development Division of FAO. The grey component calculation was based on nitrogen application rates, the leaching-runoff fraction and the agreed water quality standards for nitrate concentration. The studied crop area covered 45 provinces which were located in the Northern (13), Northeastern (19) and Central Plains (13) of Thailand. The production section was conducted in 3 starch factories. The data of water use in starch production was gathered from 24 factories (3 primary data sets and 21 secondary data sets

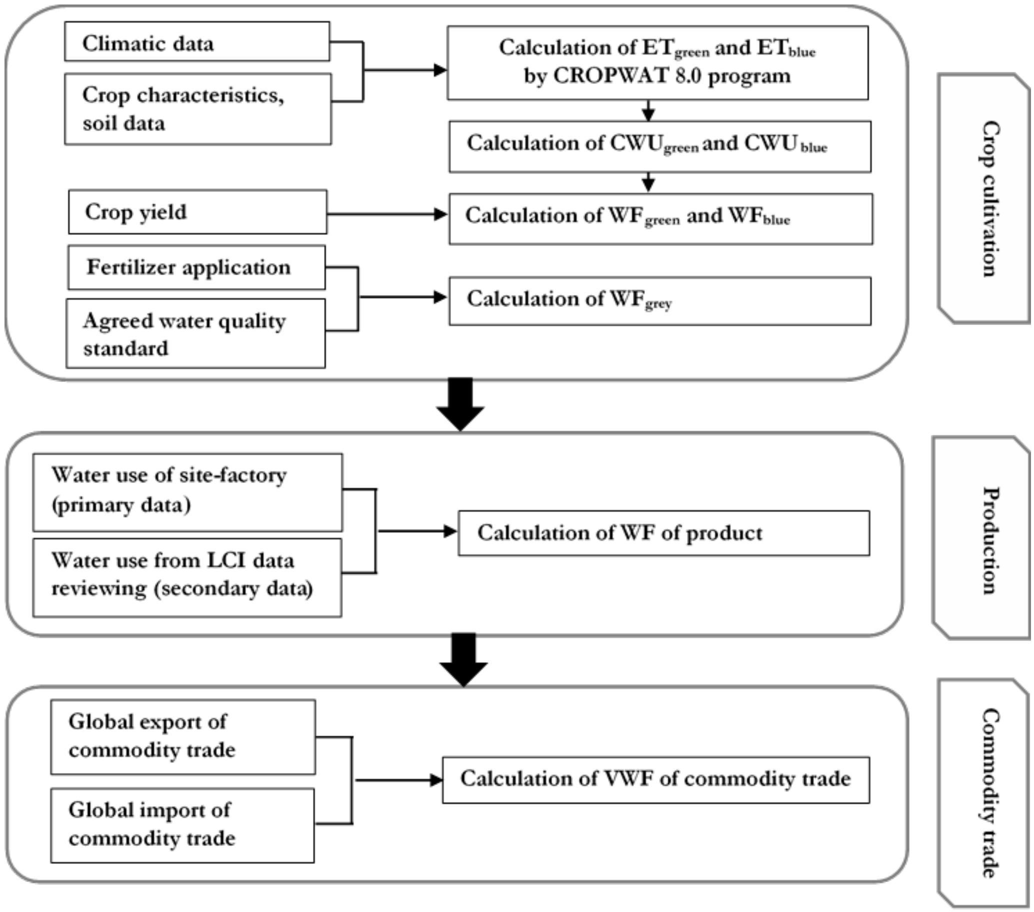


**Figure 1.** Diagram for assessment steps of water footprint and virtual water flow of cassava starch.

from Chavalparit and Ongwandee [13], Khongsiri [14], Jakrawatana *et al.* [15] and Usubharatana and Phungrassami [16]). In the last section of this study, the VWF of cassava starch was calculated by considering the flow of virtual water through the cassava starch import and export activities. However, the WF calculation did not include the water use for transportation processes both on a local and international level.

## 2.2 Water Footprint of Crop Cultivation

The global production of cassava is shown in Table 1. In Thailand, cassava is a major crop that has been cultivated in large areas. Cassava is usually planted in May and harvested in April, the following year. The total growing period is approximately 360 days. In this study, the data on fertilizer application rates recommended by the DOA was used [17]. The application of N, $P_2O_5$ and $K_2O$ fertilizers depends on soil types and crop-growing stages.

The total WF ($m^3$/ton) of cassava cultivation is calculated by the sum of green, blue and grey components, as shown below:

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

The green and blue WFs can be calculated using the Equation (2) and (3):

$$WF_{green,\ blue} = \frac{CWU_{green,\ blue}}{Y} \quad (2)$$

**Table 1.** Production of cassava worldwide (Africa, Asia, South America and the Caribbean) from 2008-2013 [2].

| Countries | Production (ton/year) | Harvested area (ha) | Yield (ton/ha) |
|---|---|---|---|
| **Africa** | **139,205,087** | **13,354,180** | **10.42** |
| Nigeria | 44,747,456 | 4,608,732 | 9.71 |
| DR Congo | 14,922,104 | 1,839,925 | 8.11 |
| Ghana | 13,643,979 | 872,305 | 15.64 |
| Others | 65,891,548 | 6,033,218 | 10.92 |
| **Asia** | **81,669,037** | **4,056,207** | **20.13** |
| Thailand | 25,918,738 | 1,255,541 | 20.64 |
| Indonesia | 23,284,772 | 1,155,361 | 20.15 |
| Viet Nam | 9,304,553 | 535,642 | 17.37 |
| Others | 23,160,974 | 1,109,663 | 20.87 |
| **South America** | **31,084,034** | **2,321,245** | **13.39** |
| Brazil | 24,325,398 | 1,731,942 | 14.05 |
| Paraguay | 2,398,675 | 176,084 | 13.62 |
| Colombia | 2,119,337 | 204,480 | 10.36 |
| Others | 2,240,624 | 208,739 | 10.73 |
| **Caribbean** | **2,047,680** | **375,970** | **5.45** |
| Haiti | 433,842 | 97,800 | 4.44 |
| Cuba | 421,089 | 68,518 | 6.15 |
| Dominican R | 168,909 | 21,667 | 7.80 |
| Others | 1,023,840 | 187,985 | 5.45 |
| **World** | **254,005,838** | **20,107,602** | **12.63** |

$$CWU_{green,\ blue} = 10\sum_{d=1}^{lgp} ET_{green,\ blue} \qquad (3)$$

Where, $CWU_{green,\ blue}$ ($m^3$/ton) is the crop water use of green or blue, $Y$ (ton/ha) is the crop yield, $ET_{green,\ blue}$ (mm/day) is the daily evapotranspiration, *lgp* (days) is the length of growing period, and the factor *10* is applied to convert the unit from mm into $m^3$/ha. The $ET_{green,\ blue}$ values for each province were estimated by using the CROPWAT 8.0 software program. The data required to estimate the evapotranspiration i.e. climatic data, crop characteristics and soil data were obtained from different sources (Table 2).

The grey WF based on the use of nitrogen fertilizer was calculated by using the equation (4):

$$WF_{grey} = \frac{(\alpha \times AR)/(C_{maximum} - C_{natural})}{Y} \qquad (4)$$

Where, $AR$ (kg/ha) is the nitrogen fertilizer application rate per hectare, α is the leaching-runoff fraction, $C_{maximum}$ (kg/$m^3$) is the maximum acceptable concentration, $C_{natural}$ (kg/$m^3$) is the natural concentration for the pollutant considered, and $Y$ (ton/ha) is the crop yield.

The leaching-runoff fraction (α) equaled to 10% of the applied nitrogen fertilizers [11]. The recommended maximum acceptable concentration

**Table 2.** Parameters and data sources for calculation the evapotranspiration.

| Parameters | Data input | Data sources |
|---|---|---|
| Climatic data | - Maximum temperature (°C) | [18] |
| | - Minimum temperature (°C) | |
| | - Humidity (%) | |
| | - Sunshine hours (hours) | |
| | - Wind speed (km/day) | |
| | - Total rainfall (mm/month) | |
| Crop characteristics | - Crop coefficient ($K_c$) | [19] |
| | - Length of crop in each development stage (day) | |
| | - Root depth (m) | |
| | - Critical depletion (%) | |
| | - Crop height (m) | |
| | - Yield response factor ($K_y$) | |
| Soil data | - Total available soil moisture (mm/m) | [20] |
| | - Maximum rain infiltration rate (mm/day) | |
| | - Maximum rooting depth (m) | |
| | - Initial soil moisture depletion (mm/m) | |

of nitrate-nitrogen in surface and groundwater in relation to Thai water quality standards was 5 mg/l [21] and the natural nitrogen concentration in the receiving water bodies was assumed to be zero [11]. The amount of nitrogen fertilizer content depends on soil type i.e. 100 kg/ha for sand, sandy loam and loam; 50 kg/ha for clay loam and clay [17].

### 2.3 Water Footprint of Crop Production

A stepwise accumulative approach was used to calculate the WF. The WF of cassava starch was associated with the amount of water used in cassava crops grown through the process of cassava starch production (Figure 3). The average WF of cassava starch production was calculated using equation (5):

$$WF_{prod}[p] = \left( WF_{proc}[p] + \sum_{i=1}^{y} \frac{WF_{prod}[i]}{f_p[p,i]} \right) \times f_v[p] \quad (5)$$

Where, $WF_{prod}[p]$ ($m^3$/ton) is the WF of output product $p$, $WF_{prod}[i]$ ($m^3$/ton) is WF of input product $i$, and $WF_{proc}[p]$ ($m^3$/ton) is WF of the processing step. $f_p[p,i]$ (ton/ton) is a product fraction defined as the quantity of the output product per quantity of input product, and $f_v[p]$ (monetary unit/monetary unit) is the ratio of the market value of this product to the aggregated market value of all the outputs products obtained from the input products [11].

### 2.4 Virtual Water Flow of Crop Production Trade in Thailand

The volume of green, blue and grey VWFs of cassava starch were taken into account in the determination of VWF of cassava trade. The VWF of cassava starch export; $VWF_{exp}$ ($m^3$/year) from Thailand equals to the quantities of cassava starch that are exported; $CT_{exp}$ (ton/year) multiplies by the WF of its product; $WF_{prod}$ ($m^3$/ton) as shown follow:

$$VWF_{exp} = CT_{exp} \times WF_{prod} \quad (6)$$

Also, VWF of cassava starch import; $VWF_{imp}$ ($m^3$/year) in a country was multiplied by the quantities of cassava starch that are imported; $CT_{imp}$ (ton/year) by WF of its product; $WF_{prod}$ ($m^3$/ton) as shown below:

$$VWF_{imp} = CT_{imp} \times WF_{prod} \quad (7)$$

The net VWF of trade cassava starch; $VWF_{net}$ ($m^3$/year) was used to estimate the difference between the VWF of export; $VWF_{exp}$ ($m^3$/year) and VWF of import; $VWF_{imp}$ ($m^3$/year) as shown below:

$$VWF_{net} = VWF_{exp} - VWF_{imp} \quad (8)$$

## 3. RESULTS AND DISCUSSION

### 3.1 Water Footprint of Cassava Cultivation

The WF of cassava cultivation in three regions of Thailand (45 provinces) were calculated in this study. Data from Table 3 shows the average total WF of cassava root was 528 $m^3$/ton, which can be divided into 187 $m^3$/ton of green, 251 $m^3$/ton of blue and 90 $m^3$/ton of grey, respectively. The top 3 provinces that had the highest WF were Ubon Ratchathani, Khonkaen and Kalasin, respectively (Figure 2). In most provinces, the blue WF was higher than green and grey, which implied that there was a large section of water used for irrigation. In order to reduce the blue proportion in cassava cultivation, an alteration to the plantation period was suggested. Instead of planting in May (the beginning of rainy season in Thailand), farmers can plant earlier, 150 days before the beginning of rainy season. After 150 days, cassava reaches the development and middle states; as this which requires a high volume of water, the high amount of rainwater in the rainy reason would be beneficial. The WF of cassava cultivation in each province differed due to the variation in climate and soil conditions. However, some areas such as Chiang Rai province (Northern region), Chachoengsao, Chantaburi, Rayong and Kanchanaburi provinces (Central Plains) showed the highest green WF proportion. These provinces have intensive rainfall so less blue water is required in cassava cultivation.

**Table 3.** Average water consumption in cassava cultivation by province.

| Provinces | Cassava crop [3-4] | | | Crop water use ($m^3$/ha) | | | Water footprint ($m^3$/ton) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Harvested area (ha) | Production (ton/year) | Yield (ton/ha) | Green | Blue | Evaporation | Green | Blue | Grey | Total |
| **Northern Region** | | | | | | | | | | |
| Chiang Rai | 3,117 | 61,087 | 19.60 | 4,255 | 3,887 | 8,142 | 217 | 198 | 51 | 466 |
| Phayao | 831 | 16,921 | 20.36 | 3,919 | 4,356 | 8,275 | 192 | 214 | 98 | 504 |
| Lampang | 1,116 | 22,158 | 19.85 | 3,542 | 4,125 | 7,667 | 178 | 208 | 101 | 487 |
| Tak | 7,884 | 181,950 | 23.08 | 3,572 | 5,503 | 9,075 | 155 | 238 | 43 | 436 |
| Kamphaeng Phet | 86,159 | 1,887,862 | 21.91 | 3,610 | 4,546 | 8,156 | 165 | 207 | 91 | 463 |
| Sukhothai | 3,506 | 67,210 | 19.17 | 3,646 | 4,967 | 8,613 | 190 | 259 | 104 | 553 |
| Phrae | 720 | 14,187 | 19.70 | 3,617 | 4,356 | 7,973 | 184 | 221 | 102 | 507 |
| Uttaradit | 3,207 | 65,763 | 20.51 | 3,543 | 4,242 | 7,785 | 173 | 207 | 98 | 478 |
| Phitsanulok | 27,833 | 594,975 | 21.38 | 3,946 | 5,426 | 9,372 | 185 | 254 | 94 | 533 |
| Phichit | 1,205 | 25,212 | 20.92 | 3,816 | 4,432 | 8,248 | 182 | 212 | 96 | 490 |
| Nakhon Sawan | 46,505 | 982,626 | 21.13 | 3,933 | 4,980 | 8,913 | 186 | 236 | 95 | 517 |
| Uthai Thani | 28,509 | 596,867 | 20.94 | 3,845 | 5,324 | 9,169 | 184 | 254 | 96 | 534 |
| Phetchabun | 16,339 | 357,905 | 21.90 | 3,811 | 4,419 | 8,230 | 174 | 202 | 46 | 422 |
| Average | 17,456 | 374,979 | 21.48 | 3,773 | 4,659 | 8,432 | 176 | 217 | 86 | 479 |

**Table 3.** (Continued).

| Provinces | Cassava crop [3-4] | | | Crop water use ($m^3/ha$) | | | Water footprint ($m^3/ton$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Harvested area (ha) | Production (ton/year) | Yield (ton/ha) | Green | Blue | Evaporation | Green | Blue | Grey | Total |
| **Northeastern Region** | | | | | | | | | | |
| Loei | 33,019 | 686,446 | 20.79 | 3,916 | 4,959 | 8,875 | 188 | 239 | 96 | 523 |
| Nong Bua Lam Phu | 6,923 | 140,150 | 20.24 | 4,133 | 4,041 | 8,174 | 204 | 200 | 99 | 503 |
| Udon Thani | 32,011 | 649,393 | 20.29 | 3,941 | 4,999 | 8,940 | 194 | 246 | 99 | 539 |
| Nong Khai | 6,290 | 123,374 | 19.61 | 3,905 | 5,347 | 9,252 | 199 | 273 | 102 | 574 |
| Sakon Nakhon | 14,865 | 279,028 | 18.77 | 4,157 | 4,589 | 8,746 | 221 | 244 | 107 | 572 |
| Nakhon Phanom | 4,895 | 94,040 | 19.21 | 3,353 | 5,407 | 8,760 | 175 | 281 | 104 | 560 |
| Mukdahan | 17,703 | 345,325 | 19.51 | 3,293 | 5,852 | 9,145 | 169 | 300 | 103 | 572 |
| Yasothon | 10,166 | 209,596 | 20.62 | 3,824 | 6,475 | 10,299 | 185 | 314 | 97 | 596 |
| Amnat Charoen | 6,354 | 130,439 | 20.53 | 2,844 | 6,554 | 9,398 | 139 | 319 | 97 | 555 |
| Ubon Ratchathani | 30,788 | 612,733 | 19.90 | 3,876 | 6,992 | 10,868 | 195 | 351 | 100 | 646 |
| Si Sa Ket | 14,047 | 292,339 | 20.81 | 3,767 | 5,414 | 9,181 | 181 | 260 | 96 | 537 |
| Surin | 9,553 | 194,061 | 20.31 | 3,860 | 5,691 | 9,551 | 190 | 280 | 98 | 568 |
| Buri Ram | 32,889 | 703,862 | 21.40 | 3,681 | 5,025 | 8,706 | 172 | 235 | 93 | 500 |
| Maha Sarakham | 16,394 | 322,161 | 19.65 | 3,293 | 5,852 | 9,145 | 204 | 282 | 102 | 588 |
| Roi Et | 10,986 | 222,135 | 20.22 | 3,682 | 6,235 | 9,917 | 182 | 308 | 99 | 589 |
| Kalasin | 41,414 | 873,170 | 21.08 | 3,515 | 7,238 | 10,753 | 167 | 343 | 95 | 605 |
| Khon Kaen | 34,577 | 673,875 | 19.49 | 4,119 | 6,429 | 10,548 | 211 | 330 | 103 | 644 |
| Chaiyaphum | 60,662 | 1,217,131 | 20.06 | 3,969 | 5,349 | 9,318 | 198 | 267 | 100 | 565 |
| Nakhon Ratchasima | 287,606 | 5,807,164 | 20.19 | 3,911 | 5,303 | 9,214 | 194 | 263 | 99 | 556 |
| Average | 35,323 | 714,549 | 20.23 | 3,739 | 5,671 | 9,410 | 185 | 280 | 99 | 564 |
| **Central Plains** | | | | | | | | | | |
| Saraburi | 4,955 | 99,347 | 20.05 | 3,875 | 5,793 | 9,668 | 193 | 289 | 50 | 532 |
| Lop Buri | 26,650 | 542,882 | 20.37 | 3,650 | 5,759 | 9,409 | 179 | 283 | 49 | 511 |
| Chai Nat | 11,466 | 216,375 | 18.87 | 2,733 | 5,958 | 8,691 | 145 | 316 | 106 | 567 |
| Suphan Buri | 5,852 | 113,795 | 19.45 | 3,356 | 5,147 | 8,503 | 173 | 265 | 103 | 541 |
| Prachin Buri | 26,008 | 547,169 | 21.04 | 3,796 | 5,728 | 9,524 | 180 | 272 | 48 | 500 |
| Chachoengsao | 45,932 | 986,861 | 21.49 | 4,402 | 4,299 | 8,701 | 205 | 200 | 47 | 452 |
| Sa Kaeo | 59,892 | 1,218,292 | 20.34 | 4,130 | 4,596 | 8,726 | 203 | 226 | 98 | 527 |
| Chanthaburi | 38,847 | 806,986 | 20.77 | 4,808 | 4,115 | 8,923 | 231 | 198 | 48 | 477 |
| Rayong | 22,461 | 484,532 | 21.57 | 4,842 | 4,137 | 8,979 | 224 | 192 | 93 | 509 |
| Chon Buri | 46,252 | 1,066,571 | 23.06 | 4,199 | 5,171 | 9,370 | 182 | 224 | 87 | 493 |
| Kanchanaburi | 55,645 | 1,114,306 | 20.03 | 4,248 | 3,972 | 8,220 | 212 | 198 | 100 | 510 |
| Ratchaburi | 13,107 | 262,091 | 20.00 | 4,653 | 4,740 | 9,393 | 233 | 237 | 100 | 570 |
| Phetchaburi | 401 | 8,386 | 20.91 | 4,331 | 6,047 | 10,378 | 207 | 289 | 96 | 592 |
| Average | 27,498 | 574,430 | 20.89 | 4,079 | 5,036 | 9,115 | 195 | 241 | 79 | 515 |
| **Average of Thailand** | **27,901** | **575,972** | **20.64** | **3,863** | **5,188** | **9,051** | **187** | **251** | **90** | **528** |

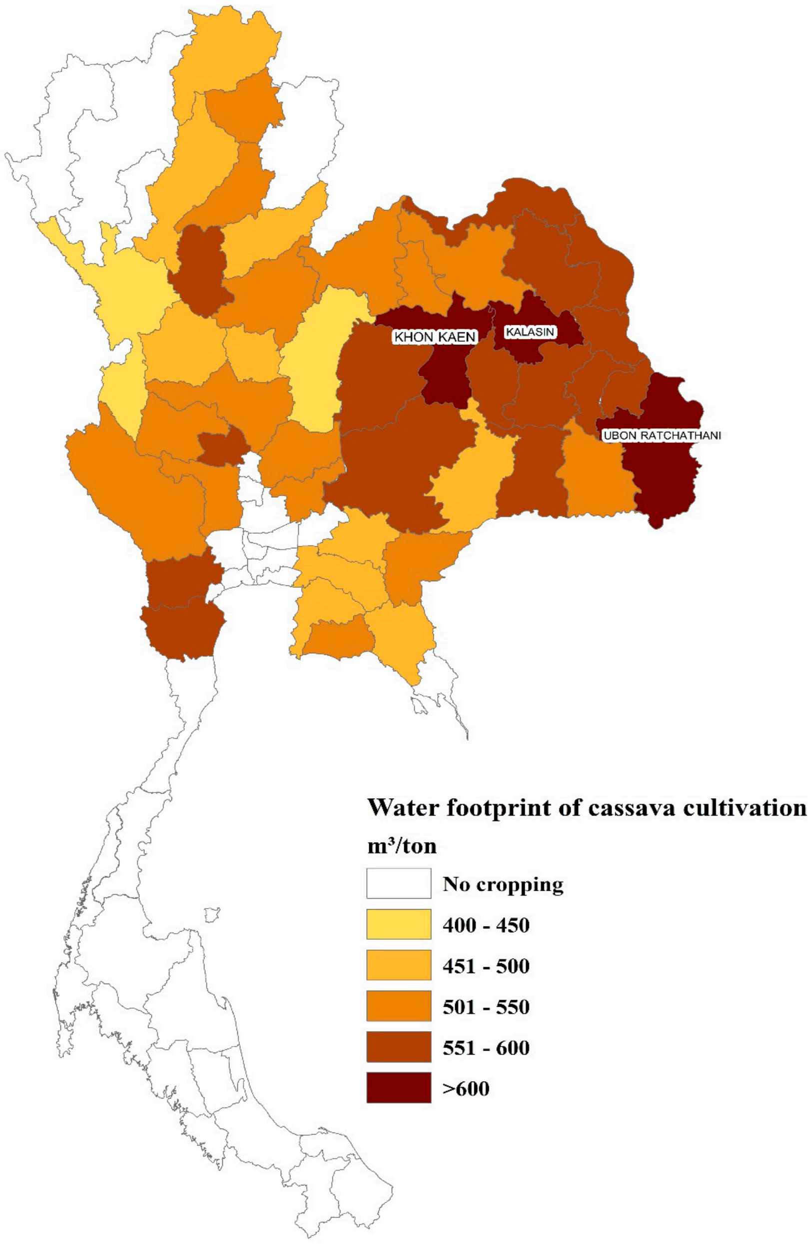


**Figure 2.** Total water footprint of cassava cultivation by province in Thailand.

The $WF_s$ of cassava cultivation of this study was compared with other studies, as shown in Table 4. The range of the total WF of cassava cultivation in Thailand was 399-599 $m^3$/ton. The results of this study were found to be similar to those of Kongboon and Sampattagul [22]. The blue component was higher than the green and grey components. Tiewtoy *et al.* [23] studied the WF in some provinces such as Chachoengsao, Chantaburi, Rayong and Chon Buri. Their results showed that the green component was higher compared to the blue component, which is similar to the result in the same area of this study. This might be because of the fact that

**Table 4.** Previous studies of the water footprint for cassava cultivation.

| References | Study area | Water footprint of cassava ($m^3$/ton) | | | |
|---|---|---|---|---|---|
| | | Green | Blue | Grey | Total |
| **Thailand** | | | | | |
| This study | Thailand | 187 | 251 | 90 | 528 |
| [22] | The Northern (13 provinces) | 192 | 232 | 85 | 509 |
| [23] | The Eastern (6 provinces) | 342 | 40 | 66 | 448 |
| [24] | Thailand | 332 | 67 | - | 399 |
| [25] | Nakhon Ratchasima province | 413 | 42 | - | 455 |
| [26] | Thailand | 415 | 184 | - | 599 |
| **Other Countries** | | | | | |
| [27] | Nigeria | 476 | 516 | - | 992 |
| [28] | Global average | 550 | 0 | 13 | 563 |

the studies were conducted under the same environmental conditions and during the same time period. These areas all experience intensive rainfall which contributes to the higher green component. Nevertheless, studies of Gheewala *et al.* [24] and Gerbens-Leenes *et al.* [25] showed that the total WF was quite low because the grey component was excluded in their studies. In addition, they found the green component was higher than the blue, which might be due to the difference in crop season. While, Pongpinyopap and Mungcharoen [26] found that the total WF (without grey) was higher than total WF from this study since they used different evaporation data using the pan evaporation method. However, the total WF of cassava cultivation in Nigeria [27] was almost 2 times higher than that of Thailand because the yield in Nigeria was lower than that in Thailand by almost 2 times. In another study, Mekonnen and Hoekstra [28] revealed the global average total WF to be 563 $m^3$/ton.

### 3.2 Water Footprint of Cassava Starch Production

To calculate the WF of cassava starch production, water consumption and wastewater generation accumulated throughout the product chain were both taken into consideration as factors. The water mass flow balance per one ton of product obtained from three cassava starch factories were used to calculate the WF of the product. In addition, the secondary data was selected from four previous studies from Thailand. Thus, the result of the average WFs of product in Thailand were calculated based on both primary and secondary data. The average water mass flow balance per one ton of cassava starch and WF calculations are mentioned in Figure 3.

It can be seen in Figure 3 that the highest volume consumed at the extraction process (7.00 $m^3$ or 40% of total water consumption in the production process) followed by roots rinsing, separating and chopping/grinding, respectively. In order to estimate the WF of cassava starch, the product fraction ($f_p$) of 0.24 (ton/ton) and the value fraction ($f_v$) of 0.87 (Bath/Baht) were used. The estimated total WF of cassava starch production of Thailand is equal to 1,945 $m^3$/ton, consisted of 678, 925 and 342 $m^3$/ton of green, blue and grey component, respectively. However, Mekonnen and Hoekstra [28] revealed that the global total WF of cassava starch was equal to 2,254 $m^3$/ton, which was similar to Thailand WF.

### 3.3 Virtual Water Flow of Cassava Starch Trade From Thailand

A large amount of cassava root is produced

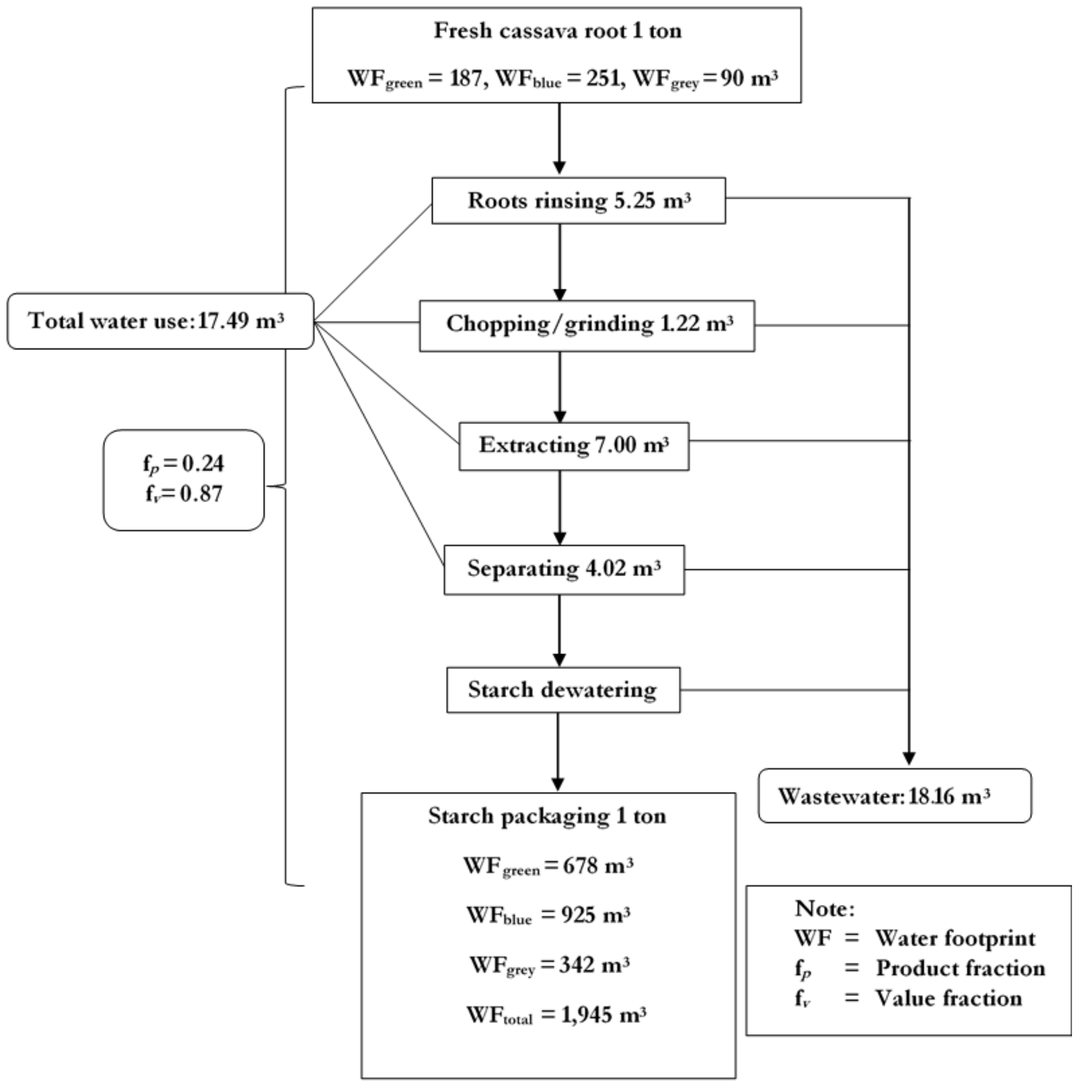


**Figure 3.** Average water mass flow balance and water footprint per one ton of cassava starch.

nationally. Fifty-five percent of the total amount of cassava root is further processed to starch. More than 65% of the cassava starch was exported to other countries worldwide [5]. The OAE [29] reported that during the years 2008-2013, the five largest countries that imported cassava starch were China (31%), Indonesia (18%), Taiwan (14%), Malaysia (10%) and Japan (7%), respectively. Besides, there were some countries that exported their cassava starch to Thailand, i.e. Lao PDR, Myanmar and Cambodia, but the quantity of these cassava starch imports to Thailand was very low compared to Thailand's export. Data on the net VWF of cassava starch exported from Thailand together with the top 20 importer countries are shown in Table 5.

A large volume of cassava starch exported from Thailand is also reflected by the enormous VWF. To assess the VWF, the WF of product and the export quantities were considered. The results show that the net total VWF related to the trade of cassava starch export from Thailand

**Table 5.** The net virtual water flow of cassava starch of export from Thailand.

| Countries | Thailand's net export (ton/year) [29] | Net virtual water flow of export (Mm$^3$/year) | | | |
|---|---|---|---|---|---|
| | | Green | Blue | Grey | Total |
| China | 589,596 | 399.75 | 545.38 | 199.28 | 1,144.41 |
| Indonesia | 339,130 | 229.93 | 313.70 | 114.63 | 658.26 |
| Taiwan | 266,108 | 180.42 | 246.15 | 89.94 | 516.51 |
| Malaysia | 194,744 | 132.04 | 180.14 | 65.82 | 378.00 |
| Japan | 128,779 | 87.31 | 119.12 | 43.53 | 249.96 |
| Philippines | 54,384 | 36.87 | 50.31 | 18.38 | 105.56 |
| Singapore | 48,501 | 32.88 | 44.86 | 16.59 | 94.33 |
| USA | 43,482 | 29.48 | 40.22 | 14.87 | 84.57 |
| Bangladesh | 30,275 | 20.53 | 28.00 | 10.35 | 58.88 |
| South Korea | 28,577 | 19.38 | 26.43 | 9.77 | 55.58 |
| Hong Kong | 24,377 | 16.53 | 22.55 | 8.34 | 47.42 |
| Australia | 16,544 | 11.22 | 15.30 | 5.66 | 32.18 |
| South Africa | 16,171 | 10.96 | 14.96 | 5.53 | 31.45 |
| Saudi Arabia | 12,513 | 8.48 | 11.57 | 4.28 | 24.33 |
| Netherlands | 11,636 | 7.89 | 10.76 | 3.98 | 22.63 |
| India | 7,407 | 5.02 | 6.85 | 2.53 | 14.40 |
| New Zealand | 6,384 | 4.33 | 5.91 | 2.18 | 12.42 |
| Russia | 5,907 | 4.00 | 5.46 | 2.02 | 11.48 |
| Vietnam | 5,567 | 3.77 | 5.15 | 1.90 | 10.82 |
| UAE | 5,112 | 3.47 | 4.73 | 1.75 | 9.95 |
| Others | 61,337 | 41.59 | 56.74 | 20.98 | 119.31 |
| **Total** | **1,896,531** | **1,285.85** | **1,754.29** | **642.31** | **3,682.45** |

to other countries was 3,682.67 Mm$^3$/year, consisting of green (1,285.85 Mm$^3$/year), blue (1,754.29 Mm$^3$/year) and grey (642.31 Mm$^3$/year), respectively. China as the largest importer, gained 1,144.41 Mm$^3$/year of VWF. Indonesia, Taiwan, Malaysia and Japan gained 658.26, 516.51, 378.00 and 249.96 Mm$^3$/year, respectively. The VWF of cassava starch from Thailand not only flows to other countries in Asia but also to some countries outside of Asia (Figure 4), for example, the USA (84.57 Mm$^3$/year), Netherlands (22.63 Mm$^3$/year), Russia (11.48 Mm$^3$/year), Australia (32.18 Mm$^3$/year) and South Africa (31.45 Mm$^3$/year). However, there was VWF of cassava starch imported to Thailand. Lao PDR was found to be the largest import source to Thailand that contributed 0.65 Mm$^3$/year, followed by Myanmar (0.33 Mm$^3$/year) and Cambodia (0.32 Mm$^3$/year). The fact that Thailand contributed up to 90% of the cassava starch exported worldwide [2] reveals that it has drained a large volume of water in the form of VWF of cassava starch trade annually. Although the original source of cassava crop is mostly produced in Central and Southeast Asia, many countries do not produce enough and consume what they produce themselves. The net VWF of

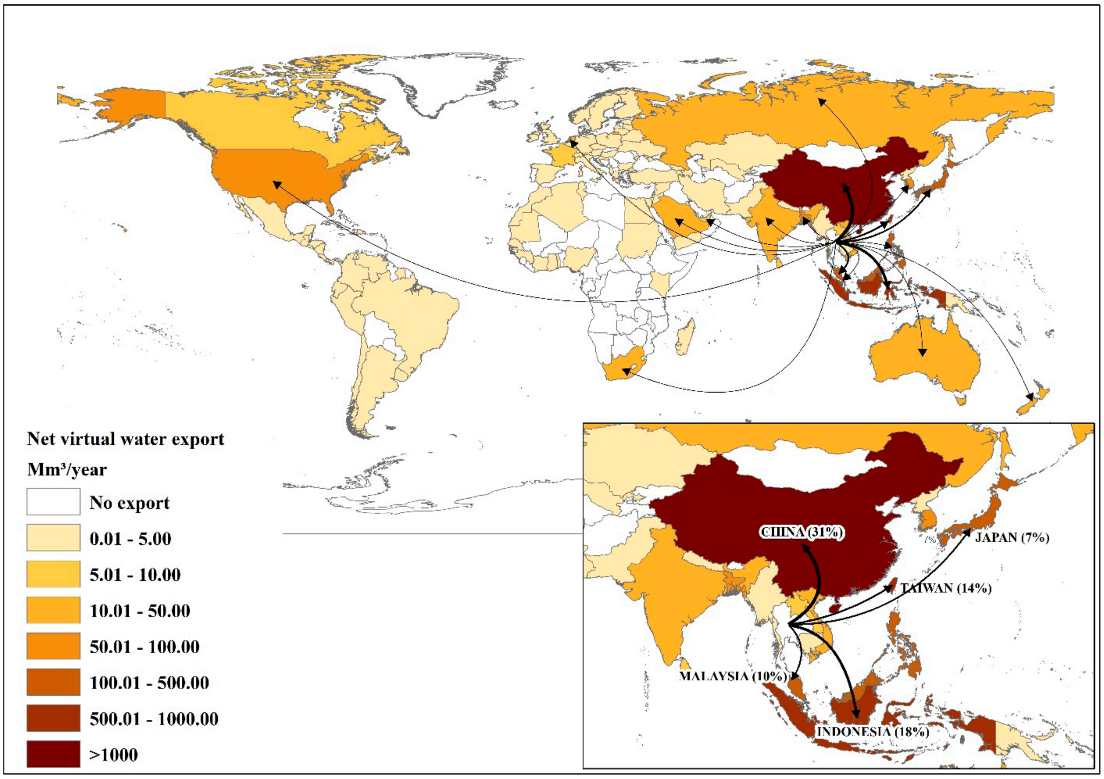


**Figure 4.** Net virtual water flow of cassava starch export from Thailand.

cassava starch trade from Thailand can be used to highlight how much water (especially from surface water resources) is used to produce cassava starch for exportation. The water use for agricultural practices throughout the manufacturing process implies the amount of freshwater flowed out of Thailand to another country.

## 4. Conclusions

By assessing the water footprint of cassava cultivation, starch production and worldwide trade, we can conclude that a large volume of water is used in cassava cultivation and processing. The water is used in cassava cultivation in the form of irrigated water, rainwater and water that assimilates pollution. For starch production, water is used in root rinsing, chopping/grinding, extracting and separating. In the trade activity, Thailand has lost a large volume of water in the form of VWF to other countries. Concerning WF of agricultural activity, a high volume of water is used to irrigate the cassava fields. This "blue" component of WF could be reduced by fixing a more appropriate planting date and crop area which is related to the soil condition and climate. Generally, crops with a high production yield (put unit) have smaller water use (put unit). Good agricultural management should be practiced in order to reduce the WF in this section. For example, soil nourishment by adding suitable nutrients, the selection of good size quality of cassava cutting stem, the application of the appropriate pest control methods [30], planting of short-lived ground cover crops such as legumes in order to decrease water evaporation and increasing soil minerals [31]. Moreover, the WF of starch production can be reduced by improving technology or making changes to the operation process. Water-saving policies should be enforced and complied with in the starch production process, especially in relation to the step that utilizes the highest volume of water. The cassava starch trade information was used to calculate the VWF. The large amount of cassava exported from Thailand implies that the country loses an enormous amount of water annually. The loss of VWF has an impact on the local environment. Thailand, as an agricultural country, needs to balance the flow of water as this is one of the most important national resources. On the other hand, countries that import cassava starch have gained VWF. The Import of starch instead of cultivation and processing in their own respective countries would help conserve water resources in water-scarce countries.

The findings from this research could be used as a part of WF database and also help in the planning of water management in Thailand. In particular, the finding can be used to create a broad picture of water use in relation to 3 important aspects of cassava related activities; planting, manufacturing and exporting, which could be of benefit for the Thai government to set policies on these topics. For example, the policies on planting duration, the technologies that help reduce the water consumption in the manufacturing process, and the amount of cassava exported internationally.

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