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RESEARCH ARTICLE

Water Footprint Analysis of Different Techniques of Cocoa Propagation

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Abstract

The nursery phase plays a crucial role in rejuvenating cocoa plantations as it significantly impacts the quality and productivity of the mature trees in the field. However, despite its significance, there remains a lack of understanding regarding its contribution to the water footprint (WF) in cocoa production. This study aims to assess the WF of various propagation techniques to promote sustainable nursery practices. Data on nurseries were collected at the Indonesian Coffee and Cocoa Research Institute in Jember, East Java, Indonesia, from June 2017 to January 2018. The results revealed that propagation accounted for a total WF ranging from 74.28 to 319.41 $m^3.ha^{-1}$ of established cocoa trees, with an average of 186.68 m^3. This total WF consisted of 9.02 to 12.89 m^3 (7.69%) attributed to seed production and 61.39 to 283.34 m^3 (92.30%) attributed to the nursery phase. Among the different nursery techniques studied, the production of true seedlings exhibited the lowest WF, followed by side grafting. To optimize cocoa rejuvenation and minimize WF, it is crucial to carefully select the appropriate nursery technique. Further evaluation is necessary to explore the potential benefits of implementing precision irrigation techniques to reduce WF during the nursery phase. By focusing on sustainable nursery practices, we can enhance the overall sustainability of cocoa production.

Keywords: footprint assessment; grey water footprint; nursery management; seedling; sustainable production.

Introduction

The cocoa tree (*Theobroma cacao* L., Malvaceae) produces cocoa beans inside its pod, with pod sizes ranging from 10 to 15 cm in length (Rohman et al., 2019). After undergoing a series of fermentation, drying, roasting, crushing into powder, and refining, the cocoa beans are known for their rich antioxidant content and are widely used in the food and beverage industries (Shafi et al., 2018; Owen, 2013).

Indonesia holds the third position in global cocoa production, contributing 8% or 0.32 million tons of cocoa annually (ICCO, 2018). The country's cocoa production is primarily carried out by smallholders (94%), private companies (3%), and state-owned enterprises (3%) (Rubiyo and Siswanto, 2012). Although Indonesia's cocoa plantation is highly competitive in bean production on a global scale (Tresliyana et al., 2015) and relatively less vulnerable to climate change (Santosa et al., 2018a), low cocoa bean productivity remains a significant concern. According to Fahmid et al. (2018), the average productivity of cocoa in Indonesia is 175% lower than that of Malaysia and 22% lower than that of Ivory Coast.

Tree productivity in cocoa cultivation depends on factors such as genotypes, shading trees, and plant age, as highlighted by a study by ICCRI (2010). Researchers like Rubiyo and Siswanto (2012) and Saputra (2015) have observed that cocoa trees older than 25 years exhibit reduced bean production, necessitating the rejuvenation of old trees. The rejuvenation process requires the availability of high-quality seedlings or propagules. Various propagation techniques, including true seedling, grafting, and marcotting, have been widely conducted to achieve this goal (Laliberté and End, 2015).

Recently, the global cocoa market has emphasized the implementation of eco-friendly production systems (Wiryadiputra, 2013), including water conservation, which is also a critical concern for other crops like coffee (Martins et al., 2018). While evaluations on the

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water requirement of cocoa trees have been carried out (Carr and Lockwood, 2011; Naranjo-Merino et al., 2018), efforts to increase water efficiency in seedling establishment in cocoa-producing countries like Indonesia are still lacking.

The Association of Southeast Asian Nations (ASEAN) has released regional guidelines on water management in cocoa fields as part of good agriculture practices, emphasizing water resources conservation (ASEAN, 2006). One tool to evaluate water resources conservation is the water footprint (WF) (Rodriguez et al., 2015; Hoekstra et al., 2011). Lower WF in agricultural production indicates higher efficiency and environmental friendliness. For instance, Naranjo-Merino et al. (2018) reported a WF of 18,876 m3 for producing one ton of cocoa beans in Colombia, while Rodriguez et al. (2015) indicated a WF ranging from 13,475 to 23,239 m^3 in other regions, depending on cocoa tree productivity. Despite the common use of WF evaluation in the cocoa industry, the assessment of WF in propagation techniques is relatively rare.

The WF concept involves calculating the total water used to produce the final product, considering both direct water usage and indirect water consumption during the production process (Hoekstra et al., 2011). Comparing the WF value of a product provides insights into its efficiency and equity compared to others, and it also informs public policies on water resource utilization. WF is often represented using different colors, such as green (WFgreen), blue (WFblue), and grey (WFgrey) (Hoekstra et al., 2011; Rodriguez et al., 2015). WFgreen estimates tree water consumption from rainfall after accounting for losses due to tree interception and run-off water, for evapotranspiration, land evaporation, and supporting production activities. WFblue estimates water consumption from groundwater, while WFgrey estimates the water required for diluting pollutants, including fertilizers, pesticides, and other waste materials. Thus, efforts to reduce water usage in agricultural production for irrigation, minimize the use of pollutants, and improve tree productivity will contribute to WF reduction (Santosa et al., 2018b). This study evaluates the WF of different propagation methods by considering the total water used for a hectare of established trees with the objective of developing a sustainable cocoa nursery production protocol.

Materials and Methods

The research was conducted at Kaliwining Estate (located at 45 m above sea level; 8.15 ^{o}S 113.30 ^{o}E) under the management of the Indonesian Coffee and Cocoa Research Institute (ICCRI-Puslitkoka) in Jember district, East Java, Indonesia. The observation period spanned from June 2017 to January 2018. General nursery data were collected following protocols outlined by Permentan (2014), and additional information was gathered through interviews with workers and managers.

Ten-year climatic data (2007-2017) were obtained from the weather station at the ICCRI site. To simplify the water footprint (WF) calculation, the ten-year climatic data were averaged. The average minimum temperature was 21.4 ^{o}C (ranging from 19.0-22.7 ^{o}C), and the average maximum temperature was 32.7 ^{o}C (ranging from 31.7-33.4 ^{o}C). The relative air humidity averaged at 90% (ranging from 88-92%), with a wind speed of 10 km.h^{-1} (ranging from 6-20 km.h^{-1}). The average duration of intense sunlight was 5.2 hours (ranging from 4.0-6.6 hours), and the average daily irradiation was 16.7 MJ.m^{-2} (ranging from 13.4-19.8 MJ.m^{-2}). The monthly precipitation averaged 152.2 mm (ranging from 1.9-164.4 mm). The cocoa tree's water requirement, based on the estimate of Allen et al. (1998), was 3.48 mm per day (ranging from 2.73-4.11 mm per day). The study utilized the Sulawesi-1 clone as a model plant, which is a well-known national clone of bulk cocoa in Indonesia (ICCRI, 2022). Optimum cocoa production is influenced by specific climatic conditions, including the amount of rainfall, temperature, duration of sunlight, and relative air humidity, all of which affect water usage, and subsequently, the water footprint.

The water footprint evaluation followed the method proposed by Hoekstra et al. (2011), which considers green (WFgreen), blue (WFblue), and grey water (WFgrey), with the total water footprint calculated as WF = WFgreen + WFblue + WFgrey. The water was classified into different colors based on the amount of water (m^3) used for preparing the final one-hectare nursery (ha), with the final water footprint value represented in units of m^3.ha^{-1}. The WF calculation was carried out in three steps. Firstly, WF was calculated for seed production, then for seedling production in the pre-nursery stage, to produce rootstock or scion. Finally, WF was calculated for specific propagation methods (true seedling, top grafting, bud grafting, and side grafting). The total water footprint for each propagation method was summarized in Figure 1.

The WF for seed production in the field was considered over a period of approximately five months (as shown in Figure 1). True seedling nurseries lasted for four months, including germination and seedling maintenance, to produce young cocoa seedlings. These young cocoa seedlings were then ready to be transplanted into the field or used as scions or rootstocks for further main nurseries. Nursery grafting

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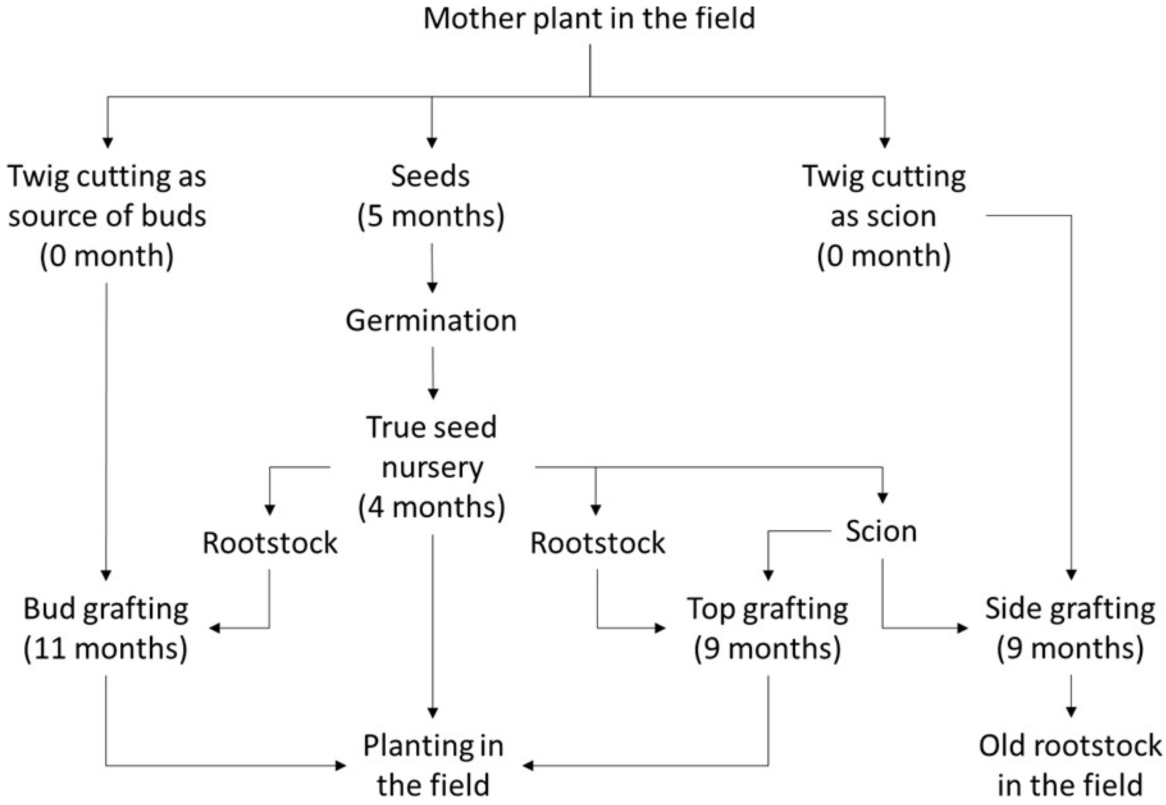

Figure 1. Diagram of scion and rootstock sources on different cocoa seedling techniques. Value in the parenthesis is the duration from grafting or nursery to the time of transplanting.

for both top and side grafting required nine months before transplanting them into the field, while bud grafting required 11 months.

In the WFgreen estimation, it was applied only in seed production for both the evapotranspiration of cocoa trees and shade trees (as shown in Table 1). WFgreen was not applicable for most seedling techniques since the process took place under a plastic house. The calculation for WFgreen is as follows: WFgreen = CWU_green / Y; where CWU_green represents the crop water use ($m^3.ha^{-1}$) and is calculated as 10 x ∑(from d=1 to lgp) of ETgreen. Here, ETgreen stands for evapotranspiration (mm per day). Y refers to seed production, measured in either tons per hectare ($ton.ha^{-1}$) or the number of seeds per hectare ($seed.ha^{-1}$), and lgp represents the length of the growth period (days). The factor of 10 is used as a conversion factor of water volume from millimeters to the water volume of a hectare ($m^3.ha^{-1}$).

For WFblue estimation, it considers water extraction from reservoirs or groundwater, as described by Hoekstra et al. (2011). Water extraction can occur through the roots of the plants or through the use of an electric pump for irrigation purposes. In cases where the water requirement (ETc) is smaller than the precipitation, the excess precipitation is considered as

Table 1. Agro-input components for direct and indirect water footprint estimation

Agro-inputs	Direct WF[1]	Indirect WF
Plant/seed	ET cocoa, shade tree	-
NPKMg fertilizers	-	Manufacturing, fertilizer pollution
Pesticide	Application	Manufacturing, pesticide pollution
Labor	-	Personal use, cleaning
Field equipment (plastic shade, hose, polybag, plastic wire)	Cleaning	Manufacturing, waste pollution

Note: [1]Direct water was used in the production process on the farm, while indirect water was used by supporting activities inside and outside the farm; ET-evapotranspiration

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reservoir or groundwater charging, with the maximum value of charging level set at 200 mm every month. However, when ETc exceeds the precipitation, the additional water required to support crop growth is considered as WFblue. The calculation for WFblue is as follows: WFblue = CWU_blue / Y; where CWU_blue represents the blue water of the plant ($m^3.ha^{-1}$) and is calculated as 10 x ∑(from d=1 to lgp) of ETblue. Here, ETblue stands for evapotranspiration of blue water (mm per day^{-1}). While WFblue can be easily calculated if a water meter is available, in the present study, it was estimated based on the amount of supplementary water used for irrigation, given the absence of a water meter.

The WFgrey represents the virtual water required for diluting pollution to an acceptable concentration by nature. This pollution includes leaching nutrients and active ingredients of pesticides that may potentially enter the water body (Hoekstra et al., 2011; Franke et al., 2013). The estimation of WFgrey follows the method proposed by Hoekstra et al. (2011) with some modifications. The formula for calculating WFgrey is as follows: WFgrey = ((α x AR) / (Cmax - Cnat)) / Y, where WFgrey is measured in $m^3.ha^{-1}$, α represents the leaching-runoff fraction, AR denotes the application rate of the active ingredient in kilograms per hectare ($kg.ha^{-1}$), Cmax stands for the maximum concentration of pollution allowed based on regulations in kilograms per cubic meter ($kg.m^{-3}$), whereas Cnat is the natural concentration of the particular chemical available in the water body in kg per cubic meter ($kg.m^{-3}$).

For pesticides, the leaching-runoff fraction (α) is considered to be 0.01 (Franke et al., 2013). The leaching-runoff fractions for P_2O_5, K_2O, and NO_3- are 0.001, 0.028, and 0.0747, respectively (Rahutomo and Ginting, 2018). For MgO and CaO, the leaching-runoff fractions are 0.06 and 0.05, respectively (Comte et al., 2012). Cnat is set as zero for most chemicals, except for Copper, for which a value of 4 parts per billion (ppb) is used, considering the allowable concentration of 1.3 parts per million (ppm) in drinking water (Calabrese et al., 2005). The values for Cmax are obtained from various sources such as the United States Environmental Protection Agency (US EPA, www.epa.gov), Ong et al. (2009), Franke et al. (2013), and Mekonnen and Hoekstra (2015). In cases where different reports provide varying Cmax values, the lowest allowable concentration is used. The allowable concentration of Mg in drinking water is set at 50 ppm (Kumar and Puri, 2012), while for deltamethrin, it is 0.1 $\mu g.L^{-1}$ (de Knecht and van Herwijnen, 2008).

The potential evapotranspiration (ETo) is calculated using Cropwat 8.0, based on the FAO Penman-Montieth equation developed by Allen et al. (1998). The crop coefficient (Kc) used for seedlings is 1.00, while for mature trees, it is 1.05 (Allen et al., 1998). The actual evapotranspiration (ETc) for the shade tree *Leucaena leucocephala* (Lam.) de Wit. (Leguminoceae) is estimated at 8.22 mm per day (Coster, 1938). The ET calculation follows the method proposed by Pasaribu et al. (2016), where ETgreen is the minimum value between ETc and Peff, and ETblue is the maximum value between 0 and (ETc - Peff). Here, ETc is calculated as Kc x ETo, where ETo represents the potential evapotranspiration in millimeters per day (mm per day), and Peff stands for effective rainfall in millimeters (mm).

In the study's limitation, the WF calculation was based on a total of 1,111 cocoa trees per hectare. Nutrients from *L. leucocephala* and cocoa tree biomass were assumed to be fully conserved in the field and were thus excluded from the analysis. In the WFgreen calculation, the precipitation water was initially allocated to the cocoa tree and then to the shading tree. Any excess precipitation water after calculating the evapotranspiration for the cocoa and shading tree *L. leucocephala* was dedicated to soil water storage, with a maximum amount of 200 mm.

Water consumption for germination was excluded from the analysis. For seedlings in the pre-nursery, daily irrigation water was set at 200 mL for the first month, increasing to 300 mL for the second and subsequent months. After grafting, each seedling received 200 mL per day for the first two months, which was then increased to 300 mL per day for the next two months, and finally 500 mL per day in the subsequent month (split into two times: morning and afternoon) until ready to be transplanted.

Water consumption by a labour was estimated at 0.1761 m^3 per day (Santosa et al., 2018b), considering the working time as 8 hours per day. In cases where the working hour was less than a day, the amount of water consumption was accumulated and converted into the working day (WD). Water used for public facilities, including visitors, was excluded from the analysis. The WD for various seedling preparation activities at ICCRI was estimated as follows: filling media into polybag required 200 unit WD^{-1}, showing seed was 4,000 holes WD^{-1}, cutting branches was 0.2 ha WD^{-1}, application of pesticide was 0.83 ha W D^{-1}, fertilizer application was 0.2 ha WD^{-1}, and seed harvest was 20 kg WD^{-1}.

In the study, the indirect WF to produce irrigation water and diesel lifting were excluded from the

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analysis, while the indirect water for the production of agrochemicals and materials were estimated from available references. For example, water to produce SP-36 and KCl was estimated at 180 L.ton^{-1} and 887 L.ton^{-1}, respectively (Durlinger et al., 2017). In cases where different values were found, such as in urea (40.6 m^3 water ton^{-1} from EAA, 2017, and 0.3 m^3.ton^{-1} from Durlinger et al., 2017), the higher value was selected. Wastewater from pesticide manufacturing and formulation was assumed to be at 204 kg.ton^{-1} active ingredient (https://www.slideshare.net/s181185/pesticide-industry-36254529). The WF for agrochemical transportation from the factory to the field was excluded from the analysis. Water for agrochemical applications was recorded, and water for nutrient dilution was calculated based on the active ingredient(s). Plastic used for shade houses, including polybags, was assumed to be single use. Although polybags were commonly burnt after use, the study considered 187 m3 of water required for assimilating each ton of plastic waste (Zygmunt, 2007).

Results and Discussion

Seed Production

The seeds used for seedling production were obtained from a special field at ICCRI dedicated to mother plant conservation. The area allocated for this purpose maintained a standard population of 1,111 trees per hectare, and the age of the trees in the field ranged from 10 to 20 years. The cultural techniques employed in the seed production field were similar to those used for cocoa bean production. Fertilizers, including urea (46% N), SP-36 (36% P_2O_5), KCl (60% K_2O), and kieserite (20% MgO), were applied annually at rates of 220 g, 180 g, 170 g, and 120 g per plant, respectively, and were split into three applications throughout the year. Additionally, the insecticide deltamethrin was applied at a concentration of 0.5 mL.L^{-1}, and it was applied twice a year. However, no supplementary watering was applied in the field, relying solely on rainfall for irrigation.

The annual seed production was 300 kg.ha^{-1}, equivalent to 0.3 million seeds per ha. This production level was considered lower than the average cocoa bean production, which is around 800 kg.ha^{-1} (Rubiyo and Siswanto, 2012). In seed production, high-quality seeds accounted for 30% of the total seeds in a pod (approximately 20 seeds), indicating a selection rate of 30% (as shown in Table 2).

For the calculation of the water footprint (WF) in seed production at ICCRI (Indonesian Coffee and Cocoa Research Institute), we considered the average time from flowering (anthesis) until seed harvest to be 150 days or approximately 5 months. However, it's important to note that the duration of seed maturation can vary depending on the specific clone being cultivated, as reported by Baharudin in 2011.

In the WF calculation, we included various factors such as the application of chemicals and fertilizers, the labour of workers, and the water used for the maintenance of mother plants. Additionally, the water consumption associated with shade-trees (*L. leucocephala*) was considered, assuming a population of 555 plants ha^{-1}, as part of the WF for seed production. However, it is worth mentioning that the WF for the establishment of the mother plants, which includes land preparation and seedling

Table 2. Characteristics and inputs of seed production, germination and nursery

Characteristics/ inputs	Seed production	Germination	Nursery			
			True seedling	Top grafting	Bud grafting	Side grafting
Duration (months)	5	0.1	4	13	13	9
Selection rate (SR,%)[1]	30	90	80	80	80	80
Watering[2]	Rainfall	Irrigation	Irrigation	Irrigation	Irrigation	Rainfall
Pesticide appl.	2 times	No	2 times	5 times	5 times	No
Fungicide appl.	2 times	No	2 times	5 times	5 times	Yes
N-P-K-Mg fertilizers[3]	Yes	No	Yes	Yes	Yes	Yes
Location of activity	OF	PH	PH	PH	PH	OF
Growing media	Original soil	SSM bed	SSM bag	SSM bag	SSM bag	Original soil

Note: [1]Selection rate was calculated from final delivery; [2]Irrigation means artificial watering; [3]Fertilizer for seed production was determined as one-third of annual application rate; OF-open field, PH-plastic house, SSM-mixed of soil:sand:manure (2:1:1).

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production, was excluded from the calculation.

The replanting activity at ICCRI takes place during the rainy season, usually around the first week of October. Consequently, the seed collection from mother plants occurs approximately in April for true seedlings and in July for grafted seedlings. The preparation time for true seedlings is 4 months, while grafting requires an additional 9 months before the seedling is ready for transplantation to the production field (Table 1).

The seedling production process at ICCRI involves two main techniques: true seedlings and grafting (Figure 2). Each seedling technique requires different agricultural inputs, has its own success rates, and varies in the preparation time, as detailed in Table 1. In the case of grafted seedlings, most rootstocks are derived from true seeding, while the scion can either come from true seedlings or branch cuttings (entres). This approach allows for the propagation of different cassava and tropical root crop clones efficiently and effectively.

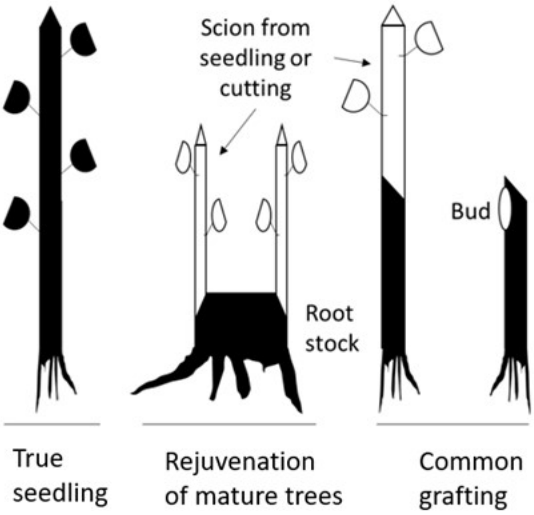

Figure 2. Diagram of different techniques for cocoa rejuvenation

The seed germination process took place in a germination bed, where seeds typically germinated within 3-5 days, mostly within 3 days (Table 1). Only seeds showing uniform germination, shape, and healthiness were selected for further steps, and approximately 90% of the sowed seeds were chosen for progression (selection rate - SRg was 90%). As the germination process utilized minimal water and tools, its contribution to the water footprint (WF) was neglected.

After germination, the seeds were transplanted into polybags under a plastic house (Table 1). Assuming a planting distance of 3 m x 3 m for mature cocoa plants in the field, the basic population in the production field was 1,111 plants per hectare. However, the number of prepared seedlings considered a 20% failure during nursery (SRs=80%) and a further 20% replacement in the field for dead plants (SRd=80%) based on Karmawati et al. (2010). Therefore, for one hectare of cocoa plantation, 1,898 seeds were prepared (rounded to 1,900 seeds for ease of calculation).

Top and bud grafting methods used 4-month-old true seedlings as rootstock. For top grafting, the scion was commonly sourced from true seedlings, and both the rootstock and scion were prepared simultaneously, effectively doubling the number of germinated seeds. Sometimes, scions were obtained from cuttings of plagiotropic branches collected from the mother plant, like material used for budding. The WF value of the plagiotropic branch was disregarded as it was considered waste. After grafting, both top and bud grafting required 9 months for perfect joining and establishment before being ready for planting in the field. The success rate of top grafting (SRt) and bud grafting (SRb) was 80%. The transplanting success rate (SRd) was also 80%. Therefore, the number of ready-to-deliver grafted seedlings for one hectare was 1,389. Considering 80% of each SRt and SRb, the number of prepared rootstocks ready for grafting was 1,736 seedlings. Consequently, the number of germinated seeds was 2,169, meaning that 2,410 seeds were prepared for bud grafting and 4,820 seeds for top grafting (2,410 for each rootstock and scion). Similarly, using the same calculation, one hectare of established cocoa trees using side grafting required 4,820 seedlings (two scions for one stump).

All seedlings were fertilized with NPK (2:1:2) monthly. The NPK source comprised urea (46% N), SP-36 (36% P_2O_5), and KCl (60% K_2O). The fertilizer mix was applied through side dressing. One-month-old seedlings received 1 g of NPK, and the rate gradually increased by 1 g each consecutive month until the fourth month. Afterwards, the application rate remained constant at 4 g of NPK per seedling until transplanting.

The water footprint of cocoa seed production varied depending on the time of seed collection (April or July) and ranged from 9.02-12.89 $m^3.ha^{-1}$ (Table 3). The WFgrey during seed production was 0.86 $m^3.ha^{-1}$. Seeds collected in April had higher WF values than those collected in July, with April seeds consuming more green water but less blue water. The higher blue water consumption of seeds collected in July was attributed to increased tree evapotranspiration and lower precipitation.

Variations in WF values among propagation

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Table 3. Water footprint in seed production and different propagation techniques

Propagation technique	Water footprint ($m^3.ha^{-1}$)			
	Green	Blue	Grey	Total
Seed harvesting time				
April	9.38	2.65	0.86	12.89
July	3.97	4.18	0.86	9.02
Nursery				
Side grafting-seedling[1]	60.44	17.80	7.77	86.01
Bud grafting	7.95	194.10	15.19	217.23
Top grafting-plagiotrop[2]	7.95	216.01	12.51	236.48
Top grafting-seedling	15.89	283.03	20.49	319.41
True seedling	9.38	61.27	3.63	74.28
Average nursery	20.32	154.44	11.92	186.68

Note: [1]Scion from seedling; [2]Rootstock from seedling and scion from plagiotropic branch

techniques were evident (Table 3). Cocoa propagation required 74.28-319.41 m^3 of water for one hectare of established plants, with an average of 186.68 m^3. True seedlings required the lowest amount of water (74.28 m^3), followed by side grafting (86.01 m^3). Excluding WF from seed production, WF during nursery maintenance ranged from 61.39-283.34 m^3. Top grafting using seedlings as scions had the highest WF, whereas WF values were reduced when using plagiotropic branches as scions.

Across the various nursery techniques, blue water was found to contribute the highest amount to the water footprint, followed by green and grey water (Table 3). However, in the case of side grafting, it was observed that the contribution of green water was higher than that of blue and grey water, accounting for 70%, 21%, and 9%, respectively (Fig 3). This higher green water requirement of side grafting is likely attributed to the Evapotranspiration (ETc) from the stump, which is assumed to be 10% of the mature tree's ETc. It is worth noting that this assumption might have resulted in the relatively high green water consumption of side grafting.

To gain a more accurate understanding of the green water consumption of side grafting, it would be beneficial to conduct further research and evaluate the ETc using specialized devices or instruments that can provide precise measurements. By employing such tools, the real green water consumption of side grafting can be assessed, leading to a better understanding of the water footprint associated with this particular nursery technique. This kind of research and data would be valuable for optimizing water usage and improving the overall efficiency of side grafting as a propagation method for cocoa plants in the future.

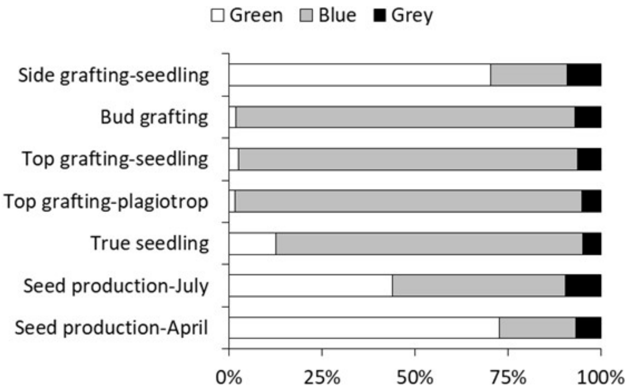

Figure 3. Proportion of green, blue, and green WF from different seed productions and nursery techniques

Figure 3 highlights the significant role of blue water as a crucial contributor to the water footprint during the seedling stage of cocoa production. On average, the contributions of green, blue, and grey water to the total water footprint were approximately 11%, 83%, and 6%, respectively. The relatively low percentage of green water (ranging from 2% to 13%) and high percentage of blue water (ranging from 82% to 93%) in grafting methods other than side grafting can be attributed to the use of plastic roofs and supplemental irrigation, which promote efficient water usage in these methods. Green water in grafting methods is derived from seed production.

The study also differentiated between direct and indirect water in the water footprint. Total direct water was found to be higher than indirect water in both seed and seedling productions, regardless of the nursery techniques used (Fig 4). Specifically, direct water contributed to 98-99% of the water footprint in seed production and 77-93% in seedling production.

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On average, the total direct water footprint for seed production was 10.81 $m^3.ha^{-1}$, while for seedling production, it was 162.67 m3 per hectare. In contrast, the average total indirect water footprint was 0.15 m^3 per hectare for seed production and 16.80 $m^3.ha^{-1}$ for seedling production.

Among the various nursery techniques, side grafting stood out with the lowest contribution of direct water, accounting for 77% of the water footprint. This suggests that side grafting is relatively more water-efficient compared to other grafting methods and seedling production techniques.

Overall, this information provides valuable insights into the distribution of water consumption during the seed and seedling stages of cocoa production, highlighting the significance of blue water and direct water usage. Understanding these aspects can aid in developing strategies to optimize water usage and improve sustainability in cocoa seedling production.

In Table 4, it is evident that the direct water footprint (WF) comprises green, blue, and grey WF, while the indirect water footprint consists of blue and grey WF. Among the components of direct water, WFblue was dominant in most nursery techniques, except for the side grafting technique. This dominance of WFblue indicates that the nursery operations at ICCRI heavily rely on groundwater as a water source for irrigation and other purposes.

Additionally, direct WFgrey also contributes significantly to cocoa seedling production, with exceptions in the case of side grafting and true seedlings. The high contribution of direct WFgrey is primarily associated with the dilution of leaching NPK fertilizers applied to the seedlings. Leaching refers to the process by which water carries dissolved nutrients (in this case, NPK fertilizers) through the soil, potentially leading to loss or runoff of these nutrients. As a result, additional water is required to prevent excessive nutrient concentration in the root zone and ensure proper nutrient availability for the seedlings.

It's worth noting that side grafting and true seedlings display relatively lower direct WFgrey compared to other nursery techniques, which could be attributed to different management practices, nutrient application methods, or specific characteristics of these techniques that contribute to reduced nutrient leaching and subsequent water requirements.

Overall, the analysis of direct and indirect water footprints in cocoa seedling production provides valuable insights into water usage patterns and can help identify areas for water efficiency improvements, sustainable water management practices, and the optimization of fertilizer application to minimize water consumption while ensuring healthy seedling growth.

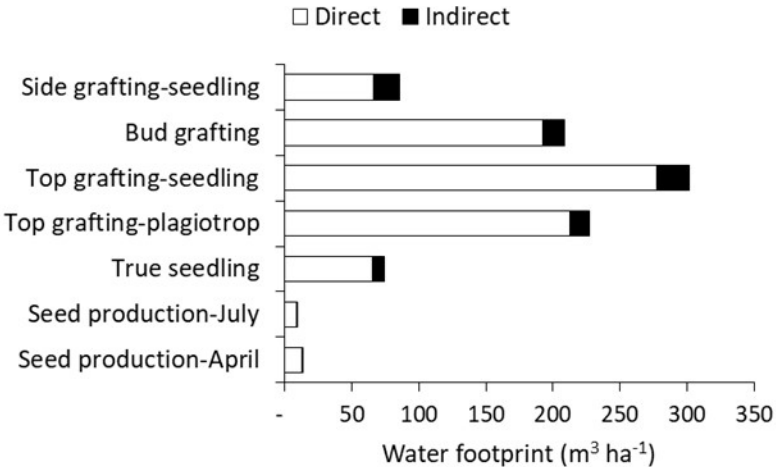

Figure 4. Total water footprints from different seed productions and nursery techniques

To develop sustainable nursery management with a low water footprint (WF), improvements are needed in both seed production and nursery techniques. In seed production, the main contributors to direct water of green and blue WF are the cocoa trees and shade trees (Table 5). For one hectare of established plants, the mother plant of cocoa consumes approximately 567.3- 635.4 m^3 of water, while the shade tree consumes approximately 698.0-1,241.2 m^3 of water. This indicates that the water use for shade trees is nearly double that of cocoa trees. To put this in perspective, the WF value in cocoa bean production is relatively high compared to crops like oil palm, ranging from 13,475-23,239 $m^3.ton^{-1}$ of beans. The specific WF value in cocoa bean production depends on various factors, such as the production site, environmental conditions, and production technology. Different crops have different WF characteristics, as

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Table 4. Direct and indirect green, blue, and grey water footprint from different propagation techniques

Propagation technique	Direct WF ($m^3.ha^{-1}$)			Indirect WF ($m^3.ha^{-1}$)		
	Green	Blue	Grey	Green	Blue	Grey
Seed harvesting time						
April	9.38	2.50	0.86	-[1]	0.14	0.00
July	3.97	4.04	0.86	-	0.14	0.00
Average seed production	6.68	3.27	0.86	-	0.14	0.00
Nursery						
Side grafting-seedling	60.44	2.74	2.81	-	15.05	4.95
Bud grafting	3.97	175.70	12.58	-	14.21	1.75
Top grafting-plagiotropic	3.97	198.50	9.91	-	13.33	1.75
Top grafting-seedling	7.95	254.08	15.40	-	20.59	3.37
True seedling	9.38	54.04	1.84	-	7.22	1.79
Average nursery	14.15	98.80	6.32	-	10.10	1.94

Note: [1]Considered as zero

highlighted by Hoekstra et al. (2011).

Efforts to reduce the WF in seed production can be directed towards both the cocoa trees and the choice of shade trees. Under shading, cocoa trees tend to have higher water use due to extensive vegetative growth, as mentioned by Kohler et al. (2009). Therefore, proper pruning practices to maintain water use efficiency in seed production become important. Additionally, careful selection of shade trees to reduce water consumption is necessary. For example, *Leuceuna leucocephala* (Leguminoceae) is considered the most water-inefficient among shade trees, consuming around 3,000 mm of water annually, according to IPOA (2017). Opting for more water-efficient shade trees like *Gliricidia sepium*, which consumes around 475 mm of water annually, as reported by Kohler et al. (2009), can help decrease water transpiration.

Applying proper cocoa-shade tree combinations has been shown to decrease water transpiration, such as using cocoa with *Erythrina poeppigiana* and *Cordia alliodora* in Costa Rica, as reported by Imbach et al. (1989).

Lastly, it is important to prevent nutrient leaching from the field to reduce the grey water footprint in seed production, as demonstrated in the case of oil palm by Santosa et al. (2018b). Overall, adopting these sustainable practices can contribute to reducing the water footprint in cocoa seed production and nursery management.

Furthermore, it is evident from Table 4 that the indirect blue water footprint was high across all seedling techniques. The primary contributors to this indirect blue water footprint were labour and the manufacture of agro-input components, as shown in Table 5 and

Table 5. The components of direct and indirect water footprint (WF) calculation in seed production in July 2017.

Component considered in WF calculation	Direct WF ($m^3.ha^{-1}$)			Indirect WF ($m^3.ha^{-1}$)		
	Green	Blue	Grey	Green	Blue	Grey
Fertilizer assimilation	-[1]	-	26.1	-	-	-
Pesticide assimilation	-	-	71.0	-	-	-
Application agrochemicals	-	-	2.9	-	-	-
Cleaning tools	-	-	-	-	-	100.0
Labor	-	-	-	-	76.3	-
Manufacturing agro-inputs	-	-	-	-	23.7	-
Cocoa tree	73.6	16.6	-	-	-	-
Shading tree	26.4	83.4	-	-	-	-

Note: [1]Considered as zero

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Table 6. To improve nursery management and reduce the indirect blue water footprint, there is a need to focus on labour efficiency and the use of eco-friendly materials. Research and implementation of eco-friendly materials, such as organic bags and organic fertilizers, should be further explored and studied.

The adoption of an automatic device for watering and fertilizer application can significantly reduce both indirect blue water footprint and direct blue water footprint associated with watering. This would lead to more efficient water use in the nursery. It is important to note that side grafting stands out with a relatively lower contribution of direct blue water footprint compared to other techniques (Table 4).

By utilizing organic fertilizers, organic pesticides, and biomaterials, the nursery can move towards an eco-friendlier production system, which would also result in a reduction of the grey water footprint. Previous studies, such as that by Siagian et al. (2014), have demonstrated the prospective use of biofertilizers in cocoa seedlings. The main contributor to direct grey water footprint, as shown in Table 6, is the water requirement for fertilizer assimilation. By applying organic fertilizers, it is possible to mitigate some of the leaching of pesticides, such as CuO, which are used to control vascular streak dieback. This can lead to a decrease in pesticide leaching from the field, making the overall production system more environmentally friendly.

In conclusion, adopting labour efficiency, eco-friendly materials, and organic practices in nursery management can significantly reduce both the indirect and direct water footprints associated with cocoa seedling production. By focusing on sustainability and environmental responsibility, the nursery can contribute to the conservation of water resources and promote an eco-friendlier approach to cocoa production.

The present study highlights the importance of selecting efficient nursery techniques to reduce the water footprint (WF) and promote water-saving technologies in cocoa seedling production. True seedlings and side grafting were found to have the lowest WF and are highly recommended techniques for nursery selection. However, it is essential to consider the specific advantages and requirements of each nursery method, such as timesaving, scion availability, grafting compatibility, water availability, and regional climate, in order to improve and optimize each method to reduce WF effectively.

The WF value in a nursery is significantly influenced by the nursery's success rate. Increasing the success rate would lead to a reduction in WF, while a decrease in success rate would have the opposite effect. It is crucial to recognize that setting the success rate of grafting at 80% in the study might be a weakness. The actual success rate of grafting can vary widely, depending on the method and clone used. Future studies should aim to incorporate more accurate and region-specific success rates to refine the WF calculations.

Another potential weakness in the present study was the assumption of crop coefficient (Kc) in the evapotranspiration calculation during seed production. Using a Kc value from a source that might overestimate direct green and blue WF in seed production could affect the accuracy of the results. Evaluating the WF value based on corrected Kc values from more appropriate sources, as suggested in the literature, would improve the accuracy of WF calculations in future studies.

Table 6. Percentage of each component on direct and indirect water footprint of top grafting using seedling shoot as scion.

Component considered in WF calculation	Direct WF ($m^3.ha^{-1}$)			Indirect WF ($m^3.ha^{-1}$)		
	Green	Blue	Grey	Green	Blue	Grey
Seed	100.0	3.2	11.2	-[1]	1.4	0.1
Fertilizer assimilation	-	-	62.5	-	-	-
Pesticide assimilation	-	-	26.3	-	-	-
Watering	-	96.5	-	-	-	-
Application agrochemical	-	0.3	-	-	0.1	-
Labor	-	-	-	-	66.7	-
Manufacture agro-input	-	-	-	-	31.8	-
Waste agro-tools	-	-	-	-	-	99.9

Note: [1]Considered as zero

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Overall, the average WF in the propagation method to establish 1,111 healthy cocoa trees in the field was found to be 186.68 m^3.ha-1, with side grafting and true seedlings contributing to the lowest WF values at 74.28 and 86.10 $m^3.ha^{-1}$, respectively. This is considered a relatively low WF when compared to the total WF of cocoa beans in other regions. However, more research is needed to understand the exact contribution of nurseries to the total WF of cocoa in Indonesia, as such data is currently limited.

Conclusion

The WF in cocoa nurseries varies depending on the technique used, and efforts to develop sustainable nurseries with low WF are recommended. True seedlings and side grafting are promising techniques with lower WF, but further research and improvements are needed to optimize their efficacy and address potential limitations. By focusing on water-saving nursery methods, the cocoa industry can contribute to water conservation and promote more sustainable agricultural practices.

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