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Water Footprint Analysis of Indonesian Tea: Exploring the Impact of Pesticides on the Grey Water Footprint

Miranti Ariyani[1]*, Mariska Margaret Pitoi[1], Retno Yusiasih[1],
Hilman Maulana[2], Adhi Irianto Mastur[2], Tiny Agustini Koesmawati[1],
Yohanes Susanto Ridwan[1], and Sunardi Sunardi,[3,4]

[1]*Research Unit for Clean Technology, The National Research and
Innovation Agency, Jl. Cisitu, Sangkuriang, Bandung, Indonesia*
[2]*Research Institute for Tea and Cinchona, Desa Mekarsari, Kabupaten Bandung, Indonesia*
[3]*Department of Biology, Faculty of Mathematic and Natural Sciences, Universitas Padjadjaran,
Jalan Raya Bandung-Sumedang, Jatinangor, Sumedang, Indonesia*
[4]*Graduate Programme on Environmental Studies, Postgraduate School, Universitas Padjadjaran,
Jl. Dipati Ukur No. 35, Bandung, Indonesia*

*Corresponding author: miranti.ariyani@gmail.com
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Abstract

Due to the insignificant load and improper data records, pesticides were commonly neglected from grey water footprint assessment. In this study, the impact of pesticides on water footprint value of Indonesian dried tea leaves were explored, and water sustainability was assessed from water pollution perspective. The total water footprint value was comprehensively quantified by combining the conventional and the latest grey water footprint methods. It was found that incorporating pesticides into grey water footprint assessment has corrected the ratio value of each water footprint component of tea. Grey water (27%), which usually minor, was higher than blue water (12%) but still lower than green water (60%). The total water footprint of tea was 3185.5 m³/ton product, indicating that the value has significantly lower than the previous calculation. Moreover, grey water footprint assessment in this study indicates that higher level of toxic and persistent properties of bifenthrin contributes more to the surface water pollution. Therefore, the use of pesticides with lower toxicity and shorter half-life degradation in tea production will strongly promote water sustainability.

Keywords: Indonesian tea; Water footprint; Pyrethroid; Neonicotinoid; Grey water

1. Introduction

Water is an essential resource for the supply chain's sustainability, especially in the crop-derived product industry. The water footprint is commonly used as an indicator for water sustainability assessment due to its comprehensive assessment for real and virtual water (Hoekstra *et al.,* 2009). Green, blue, and grey are the three components of water footprint. Green and blue water footprint refers to the amount of precipitation, surface, and groundwater consumed along the product supply chain through evaporation, incorporation with the product, or returns to another catchment area (Hoekstra *et al.,* 2009). Grey water footprint is defined as the amount of fresh water required to assimilate the pollutants in a water body to meet the water quality standard required by local regulation (Hoekstra *et al.,* 2009). Blue and green water footprint are known as indicators for consumptive water use, while grey water footprint is an indicator for assimilation capacity (Mekonnen and Hoekstra, 2011).

Numerous studies assessing the sustainability of water in the supply chain through water footprint assessment have been performed for crops and crop-derived products such as tomato (Ramírez *et al.,* 2015), soy (Ercin *et al.,* 2012), sweeteners and bio-ethanol (Gerbens-Leenes & Hoekstra, 2012), and cotton products (Chapagain *et al.,* 2006). Furthermore, water footprint assessment is also beneficial as a reference for decision-making, such as for management policies of the supply chain (Aivazidou *et al.,* 2016; Gheewala *et al.,* 2013) and national water policy (Aldaya et al., 2010; Pahlow *et al.,* 2015; Schyns and Hoekstra, 2014).

Although water footprint assessment of fresh and dried tea leaves have already been performed both locally and globally, their estimation usually underestimated the contribution of significant contaminant like pesticides. The water footprint of tea have been calculated globally (Jayasundara *et al.,* 2016; Jefferies *et al.,* 2012; Mekonnen and Hoekstra, 2011), and further research have already been done for Indonesia (Chapagain and Hoekstra, 2007; Jefferies *et al.,* 2012). In general, water footprint assessment of tea was performed using conventional methods (Hoekstra *et al.,* 2009) enriched with more comprehensive approach using a grid-based dynamic water balance model (Mekonnen and Hoekstra, 2011) and life cycle assessment approach (Jefferies *et al.,* 2012).

The availability of local data in water footprint assessment is essential for accurate estimation of water footprint value. Local data will avoiding deviation from total water footprint value, reducing uncertainty, and avoiding inaccuracy due to the lack of geographical specificity (Bulsink *et al.,* 2010; Jayasundara *et al.,* 2016; Lovarelli *et al.,* 2016). However, most studies about water footprint of tea in Indonesia only used average data. For example, due to the lack of climate information in the exact location of tea plantation, country-average climate or climate informations obtained from a meteorological station near the capital of crop-producing regions was used (Bulsink *et al.,* 2010; Chapagain and Hoekstra, 2004, 2007; Jefferies *et al.,* 2012).

Furthermore, most grey water footprint assessments of crops were only include fertilizers as contamination sources of surface water. Commonly, only a fraction of nitrogen was considered in the assessment as in cotton (Chapagain *et al.,* 2006), crop (Bulsink *et al.,* 2010), citrus (Munro *et al.,* 2016), and tea (Chapagain and Hoekstra, 2004, 2007; Jayasundara *et al.,* 2016; Mekonnen and Hoekstra, 2011). The low concentration and absence of pesticides application data are likely the reason for pesticides exclusion in water footprint estimation in those studies. To date, only two studies have included pesticides in the assessment. One discussed the proposed method for pesticides inclusion using each pesticide characteristics, soil characteristics, and pesticide toxicity to the aquatic organism (Paraiba *et al.,* 2014), while other (Paraiba *et al.,* 2014; Vale *et al.,* 2019) assessed the grey water footprint of pesticides mixture used in sugarcane cultivation.

Incorporating pesticides into grey water footprint assessment will accurately estimate the associated potential pollution impact related to grey water footprint value. Moreover, it is also essential since tea crop is vulnerable to pests and diseases. Insecticides such as pyrethroids, neonicotinoids, and glyphosate as herbicides, are commonly used in tea plantations. Like other developing countries, tea plantations in Indonesia use massive amounts of those pesticides to ensure the sustainability of production.

Indonesia has several pilot tea plantations as reference for all the tea cultivation activities in Indonesia. The largest one is located at the Upper Citarum watershed, West Java province. The existence of tea plantations in the Citarum watershed is important since water sustainability is the primary concern, aligning with the conservation and restoration program for the Citarum River proposed by the government. In this study, green and blue water footprint were quantified more comprehensive using conventional method (Hoekstra *et al.,* 2009) with some additions to the latest grey water footprint method (Vale *et al.,* 2019). Furthermore, for more precise assessment, local climate data was also considered as well as soil conditions, fertilizers, and pesticides application, which

were usually neglected. The aim of this study is to explore the impact of pesticides on the total water footprint of Indonesian tea and assesses water sustainability from water pollution perspective.

2.Materials and Methods

2.1 Study area

The study area was the Gambung tea plantation located in the Citarum Watershed (see Figure 1). This area was chosen since it was the largest pilot tea plantation in Indonesia with a total productive area of ± 395 ha. Based on the Schmidt and Ferguson (1951), the climate of the area is wet (type B), characterized by annual average rainfall of ± 2,562.18 mm, with the effective rainfall during all the tea cultivation stage of ± 1,425.5 mm/year.

2.2 Water footprint of tea cultivation

In this study, water footprint assessment was conducted from the initial phase of tea cultivation to the harvest in a 10-years scenario. The consumptive water use (green and blue water) and assimilative water (grey water) during the tea cultivation and production process are presented in more detail in Figure 2. All processes in the cultivation step were obtained from direct observation and interview, whereas for tea production, besides obtained through direct interview and observation, the result than validated using the mass balance of tea production obtained from secondary sources (Waluyo *et al.,* 2018).

In the cultivation step, green water resource was calculated as the amount of effective rainfall used by the plant and stored in the soil, whereas blue water was calculated as the amount of water taken up by plants from irrigation water. Furthermore, grey water footprint was calculated as the volume of surface water needed to assimilate the pesticides and fertilizers load in the surface water. Synthetic pyrethroids, including bifenthrin, permethrin, deltamethrin, and neonicotinoids such as thiamethoxam, imidacloprid, and methomyl were used as insecticides in tea cultivation. Meanwhile, glyphosate was used as herbicides. However, since imidacloprid and methomyl
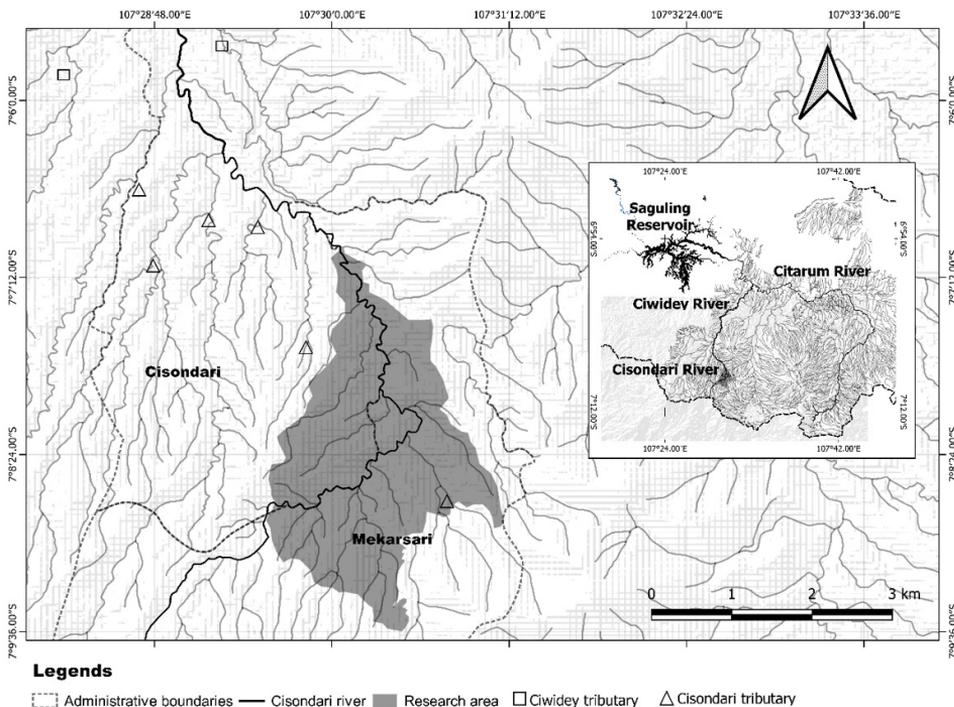

Figure 1. Tea plantation located at Citarum Watershed

were mostly used in the nursery stage in insignificant amounts, they were excluded from the assessment. Similarly, glyphosate was also excluded from the assessment due to the lack of application data. In addition, since the application of urea as fertilizer was significantly higher than phosphate and potassium chloride, the last two fertilizers were excluded from the assessment.

2.3 Green and blue water footprint

The estimation of green and blue water footprint components were referred to the water footprint assessment manual (Hoekstra *et al.,* 2011) and the water footprint manual state of the art (Hoekstra *et al.,* 2009). The green and blue water footprint were estimated by evapotranspiration value using "the crop water requirement option" since the actual irrigation data was not available. In this study, the CROPWAT 8.0 model (FAO, 2018), developed by the Food and Agricultural Organisation, was used to estimate green and blue water footprint. CROPWAT 8.0 model was employed using climate data (see Table 1), crop properties, soil characteristics (see Table 2), and crop productivity.
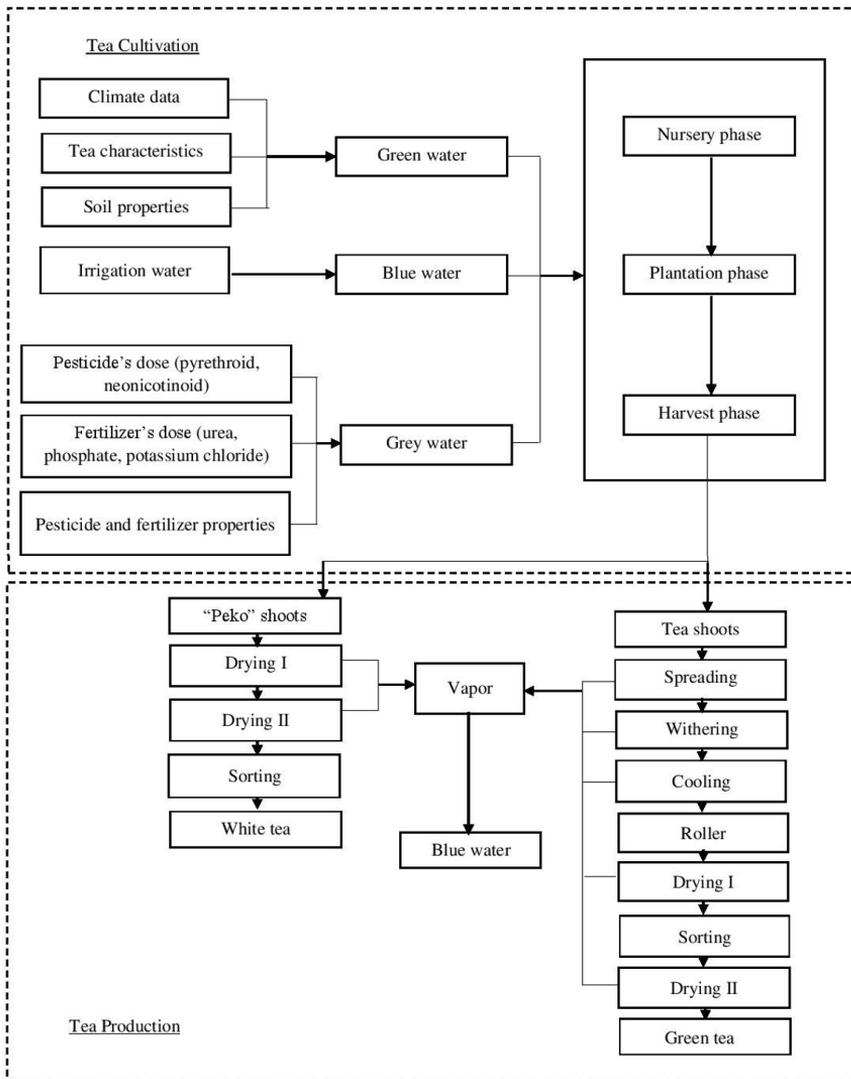

Figure 2. The diagram to calculate the green, blue, and grey water during the tea cultivation and production

The climate data, such as rainfall for the last ten years, were obtained from Automatic Weather Stations at the study location. However, due to the absence of a meteorological station near the study location, the temperature (ºC), humidity (%), wind (km/hr), and sun (hr) were estimated by the new loc-clim 1.0 using the coordinate location study as an input (FAO, 2005). The climate data generated was used to estimated the daily reference evapotranspiration (ETo) through CROPWAT 8.0 model. Since CROPWAT 8.0 only provide the daily calculation of crop water requirements using daily ETo as an input (FAO, 2018), therefore the wind speed parameter obtained from the loc-clim 1.0 model was first converted into km/day as required by the CROPWAT 8.0 model In addition, crop coefficient of tea was obtained from FAOSTAT (Chapagain and Hoekstra, 2004).

The soil characteristics and tea productivity were obtained from direct observation. The pooled topsoil (0 – 20 cm) samples were randomly collected from 11 locations in the tea plantation, represented the 11 blocks of the tea plantation area for soil characterization. The soil samples were collected from five sampling points from each site, then mixed into one composite sample. The soil texture was then characterized using the Soil Hydraulic Properties Calculator to obtain soil characteristics (see Table 2) as an input for water footprint assessment using CROPWAT 8.0. All water footprint components were divided by the tea tonnage average for the last ten years, which was about 9.4 tons per hectare. The green and blue water footprint were estimated by calculating the crop water requirement (CWR, mm/day)

Table 1. Climate data

Month	Temp (ºC)		Hum	Wind	Sun	Radiation*	Rainfall	ETo*
	Min	Max	(%)	(km/day)	(hour)	MJ/m²/day	(mm)	
January	17.4	27.3	92	97	5.1	17.6	342	3.49
February	17.4	27.7	86	97	5.3	18.1	286	3.68
March	17.5	27.6	89	97	5.8	18.6	315	3.67
April	17.7	28.0	84	99	6.2	18	333	3.62
May	17.3	27.4	80	97	6.4	16.9	314	3.36
June	16.5	27.9	79	97	6.8	16.6	109	3.27
July	15.8	27.7	80	99	7.3	17.6	47	3.39
August	15.7	28.9	73	100	7.6	19.4	57	3.90
September	16.3	29.6	71	100	7.3	20.3	108	4.25
October	16.9	30.8	65	100	6.9	20.4	224	4.52
November	17.2	30.2	86	99	6.2	19.3	307	4.06
December	17.2	27.8	80	97	5.1	17.5	251	3.70

Source: Automatic Weather Station (AWS) Gambung
*CROPWAT 8.0

Table 2. Soil characteristics

Soil characteristics	Value
Soil Texture	
Silt (%)	49
Clay (%)	25
Sand (%)	26
General soil data	
Soil organic carbon content (g/g)	0.077
Soil volumetric water content at field capacity (L/L)	0.135
Dry bulk density (kg/L)	1.347
Total available soil moisture (mm/m)	158
Maximum rain infiltration rate (mm/day)	156
Maximum rooting depth (cm)	300
Initial soil moisture depletion (%)	47.5
Initial available soil moisture (mm/m)	75.06
Water daily net recharge of the soil area (m/day)	0.119

and irrigation water requirement (IR, mm/day). CWR refers to the total water needed for evapotranspiration to meet the plant requirement, and the value is equal to evapotranspiration (Eq. (1)) if the water required for plant growth in the location study is sufficient (Hoekstra *et al.,* 2009).

$$ET_c = K_c \times ET_0 \qquad \text{Eq. (1)}$$

Kc denotes the crop coefficient of tea in a tropical area (Chapagain & Hoekstra, 2004); ETo is defined as reference crop evapotranspiration calculated by CROPWAT 8.0 using several inputs of climate data. Irrigation requirement (IR) is defined as the differences between plant evapotranspiration value (ETc) and effective rainfall (P_{eff}) and calculated throughout plant growth (Hoekstra *et al.,* 2009) (Eq. (2)):

$$IR = ET_c - P_{eff} \qquad \text{Eq. (2)}$$

The green water footprint (ET_g, mm/day) of the tea was estimated as the minimum value of evapotranspiration and effective rainfall (P_{eff}) (Hoekstra *et al.,* 2009) (Eq. (3)), whereas blue water footprint (ET_b, mm/day) of the tea was estimated as the differences between plant evapotranspiration value (ET_c) and effective rainfall (P_{eff}) (Eq. (4)).

$$ET_g = min(ET_c, P_{eff}) \qquad \text{Eq. (3)}$$

$$ET_b = max(0, ET_c - P_{eff}) \qquad \text{Eq. (4)}$$

All data obtained from the previous estimation were then used for crop water use (CWU, m³/ha). CWU was estimated by multiplying green and blue water footprint throughout plant growth by 10, defined as a conversion factor from mm to m³/ha (Hoekstra *et al.,* 2011) (Eq. (5) and Eq. (6)).

$$CWU_g = 10 \times \sum ET_g \qquad \text{Eq. (5)}$$

$$CWU_b = 10 \times \sum ET_b \qquad \text{Eq. (6)}$$

Lastly, blue and green water footprint processes were quantified by dividing each crop water use (m³/ha) value by yield (m³/ton) (Hoekstra *et al.,* 2009) as shown in Eq.(7) and Eq. (8).

$$WF_{proses,green} = CWU_g/Y \qquad \text{Eq. (7)}$$

$$WF_{proses,blue} = CWU_b/Y \qquad \text{Eq. (8)}$$

2.4 Grey water footprint

To date, methods for assessing grey water footprint for pesticides, particularly in tea, are unavailable. Therefore in this study, the latest proposed method (Vale *et al.*, 2019) was used to complement the former (Hoekstra *et al.*, 2009). Grey water footprint (m³/ton) in the cultivation stage refers to the amount of water required to assimilate the pollutant that is contaminated the ground and surface water (Mekonnen and Hoekstra, 2011).

Grey water footprint assessment for all pesticides used in the cultivation stage was adapted from Vale *et al.* (2019). Several inputs were calculated for grey water estimation. They were pesticide dose, leaching fraction of each pesticide, pesticide characteristics, soil characteristics, and pesticide toxicity to each aquatic organism (Eq. (9)).

$$GWF_{PM} = \sum_{i=1}^{n}(\alpha^i AC^i AD^i + (1-\alpha^i)AC^i AD^i AF^i)/PNEC^i \quad \text{Eq. (9)}$$

α represents the fraction of insecticide that reaches surface water. Due to the limited information of pyrethroid and neonicotinoid leaching fraction, the fraction of pyrethroid was determined from the ratio between each concentration pyrethroid in the soil (µg/kg) to maximum equilibrium concentration expected in water ($ECEW_{max}$) (µg/L). $ECEW_{max}$ represents the probable concentration of each compound in surface water which was estimated by concentration of insecticide in the soil, adsorption coefficient of each compound (Kd), organic carbon soil partition coefficient (K_{OC}), and organic carbon content (OC) as an input (Aznar *et al.,* 2017).

The leaching fraction for each neonicotinoid was obtained from various studies in several climates and soil types (Ibrahim and Al-Turki, 2020; Zhang *et al.,* 2020). AC is the cultivated area (ha); AD is the pesticide dose (kg/ha), which is obtained from the fraction of pesticide transferred to the soil (85% from applied pesticide dose) (van Zelm *et al.*, 2014); AF is the pesticide attenuation factor; PNEC (kg/m³) denotes, as predicted no effect of concentration of pesticide in water.

The PNEC was determined using an assessment factor (A_{SF}) and the lowest EC_{50} value for each aquatic organism as an input (see Table 3). In this study, an ASF of 100 for pesticides was employed to represent the conservation model intermediate (Vale *et al.*, 2019). For the PNEC and pesticide attenuation factor (AF), the formulations below were used (Eq. (10), Eq. (11), and Eq. (12)).

$$PNECi = \frac{10^{-3}}{A_{SF}} \min\{EC50i \ (algae, daphnids, fish)\} \quad \text{Eq. (10)}$$

$$A_F = exp^{\left(\frac{-kzR_F \theta_{fc}}{Jw}\right)} \quad \text{Eq. (11)}$$

$$R_F = 1 + \frac{\rho_d f_{OC} K_{OC}}{\theta_{fc}} \quad \text{Eq. (12)}$$

In which k (d^{-1}) represents the pesticide degradation rate estimated through k =ln $(2)/t_{1/2}$; $t_{1/2}$ (d) is the pesticide half-life in the soil; z (m) is soil depth defined as 2 m (Vale *et al.*, 2019); R_F (dimensionless) represents the pesticide retardation factor; θ_{fc} (L/L) is the soil volumetric water content at field capacity. The soil volumetric water content generated from the direct calculation using Soil Hydraulic Properties Calculator (see Table 2), and J_w (m/day) is the water daily net recharge of the soil area estimated through the summation of daily precipitation rate (mm/day), daily irrigation rate (mm/day), the rate of capillary rise (mm/day), the rate of deep drainage (mm/day), actual evapotranspiration rate (ET_R, mm/day) and runoff rate (RO, mm/day). Whereas ρ_d represents dry bulk density (kg/L); fOC is the soil's organic carbon content (g/g); KOC is the pesticide soil organic carbon partition coefficient (L/kg).

To calculate grey water footprint of the used pesticides, in this study, grey water for each pesticide was divided by the yield (kg/ha). All the input needed for the grey water footprint estimated from each pesticide is presented in Table 3.

Meanwhile, grey water footprint for nitrate as a contaminant from fertilizer was calculated based on Eq. (13) (Hoekstra *et al.,* 2009).

$$WF_{proc,gray} = ((\alpha \times AR)/(C_{max} - C_{nat}))/Y \quad \text{Eq. (13)}$$

In which α denotes the fraction of pollutants leached to the surface water. The 10% of nitrogen was assuming to be lost in this study (Bulsink *et al.*, 2010; Chapagain *et al.,* 2006; Mekonnen and Hoekstra, 2011) due to the unavailability of nitrogen fraction leaching database in Indonesia. AR is the amount of fertilizer used per hectare (kg/ha); C_{max} is the ambient water quality standard of nitrate in the water body (0.02 kg/m³) which is obtained from local water regulation (Government Regulation No 82, 2001); C_{nat} is a natural concentration of nitrate in the receiving water body (0.005 kg/m³) obtained from the primary analysis of nitrate and Y is tea yield (ton/ha).

2.5 Water footprint of production step

In this study, blue water footprint in the production stage is defined as the water that evaporates during the process and direct water used for all processes related to tea production (Hoekstra *et al.,* 2009). The green and white tea production data were obtained from direct interview and observation. The data obtained from green tea were then validated using the mass balance of green tea production obtained from the previous study (Waluyo *et al.,* 2018).

Table 3. Pesticide characteristics

Pesticides	Soil organic carbon partition coefficient (K_{OC})[a]	Soil degradation half-life (day)[a]	Pesticide degradation rate (d^{-1}) [a]	Toxicity (EC_{50}/LD_{50}) (mg/L)[b]			R_F
				Algae	Daphnids (*Daphnia magna*)	Fish (*Cyprinus carpio*)	
Deltamethrin	704,000	24.2	0.027	9.1	0.004	0.002[c]	5.44×10^5
Permethrin	277,000	39.5	0.017	0.004	0.001	0.015	2.14×10^5
Bifenthrin	237,000	96.3	0.007	0.38	0.001	0.058[d]	1.83×10^5
Thiamethoxam	68.4	72	0.009	97	106	120[e]	53.8

Source: [a](Laskowski, 2002); [b](USEPA, 2018) [c](Çalta and Ural, 2004); [d](Velisek *et al.,* 2009); [e]*(Finnegan et al.,* 2017)

Since the production step was not generate effluent, grey water footprint in this stage was not considered. Using a step accumulative approach (Hoekstra *et al.,* 2009), the water footprint of tea was estimated using formulation as follows (Eq. (14)).

$$WF_{prod(green,blue,grey)[p]} = \frac{[WFproc[p] \;+\; WF\,prod\,[i]]}{f_p\,[p,i]} \; x\, f_v\,[p] \quad \text{Eq. (14)}$$

WF$_{prod(green, blue, grey)[p]}$ are green, blue, and grey water footprint components for the product; WF$_{proc[p]}$ is water footprint value of the processing input into the product, whereas WF$_{prod[i]}$ is water footprint value of the input production (i), $f_p[p,i]$ is the mass loss of product (p) from the input (i) that was quantified as the ratio between the amount of product (w$_{[p]}$, ton) and the amount of input (w$_{[i]}$, ton), and $f_v[p]$ defined as the ratio between the market value of the particular product to the aggregated market value of all the product outputs. All of water footprint components from the cultivation step to the production step were then summed up using the formulation as follows (Hoekstra *et al.,* 2011) (Eq. (15)).

$$WF_{prod} = WF_{prod,green} + WF_{prod,blue} + WF_{prod,grey} \quad \text{Eq. (15)}$$

3. Results and Discussion

This study was incorporated pesticides and fertilizers into grey water footprint calculation of tea as an improvement from earlier studies (Chapagain and Hoekstra, 2004; Mekonnen and Hoekstra, 2011). As a result, the weighted average water footprint of tea was 3185.5 m³/ton, consisting of green, blue, and grey water.

Since the green and white tea were coming from a similar plant and cultivated simultaneously, the water footprint values were presented as a combination of the two, as shown in detail (Table 4).

As seen in Table 4, the consumptive water footprint of Indonesian tea was dominated by green water, which has no opportunity cost compared to blue water. Opportunity cost represents the loss of some activity benefits due to the other uses of water resources (Hoekstra and Chapagain, 2011). The social and economic impact that were generated from rainwater, represented by green water, during the crop cultivation was mainly insignificant (Chapagain and Hoekstra, 2011), or in other words, the purpose of rainwater outside the crop production was likely to result in a lower benefit; thus, the opportunity cost was negligible.

Meanwhile, blue water component contributed the lowest (393.58 m³/ton) to the total water footprint (12%). Therefore, the contribution of blue water footprint to water resources in terms of tea production was relatively marginal. Nevertheless, blue water has a greater opportunity cost and socio-environmental impact than green component (Hoekstra and Chapagain, 2011) since it might provide a higher economic and social return; therefore, blue water utilization is important for decision-making issues.

The grey water footprint value was medium in this study, accounted for 839.38 m³/ton. It represents the amount of water that is needed to assimilate the pesticides and fertilizers during tea cultivation. However, differs from the two components above, grey water does not represent the level of consumptive use

Table 4. The volume of water used in each process

Process	The volume of water (m³/ton)		
	Green	Blue	Grey
Nursery and plantation	1,952.54	386.73	
Fertilizers application (Urea, 46% N)			839.3
Pesticides application (Deltamethrin, Permethrin, Bifenthrin, Thiamethoxam)			0.04
Production stage		6.85	
Total consumptive water	1,952.54	393.58	
Total assimilative water			839.38

but the surface water's assimilative capacity due to the contaminant presence (Lovarelli *et al.*, 2016). Therefore, the value grey water footprint in this study represents the amount of fertilizers and pesticides applications that potentially leach to surface and groundwater. Unlike fertilizers, the application of pesticides in the study location depends on pests and disease attacks prior to harvesting.

Each pesticide application rate was obtained using the proportion value between the average area sprayed by pesticides and the total plantation area (see Table 5). Whereas for fertilizer, with an application rate of 1,150 kg/ha, grey water footprint was generated from urea application (46% N) and accounted for 839.3 m^3/ton.

This study shows that, by excluding grey water footprint, green water is a prominent component in crop production. By excluding grey water footprint into the estimation, the consumptive water use of fresh tea leaves in Agrabinta, Indonesia (8,540.12 m^3/ton) (Jefferies *et al.,* 2012) is larger than Gambung plantation area (3185.5 m^3/ton) (see Table 6). The difference in the proportion of water consumptive use for tea is likely to be caused by different climates, production process (drying process), and productivity of each tea type. In the former study, the yields were obtained from the FAO country average, which tended to be lower than the actual condition. A similar pattern can also be seen in the comparison between the water footprint of dry tea leaves using Indonesia climate and productivity data average (Chapagain and Hoekstra, 2007), where the consumptive water footprint value obtained was six times larger than the present study. The difference in value mainly came from the climate, soil characteristics, and tea tonnage, which was lower 5.5 ton/ha than our present study.

Moreover, so far, only two studies of water footprint of tea included grey water footprint in their assessment (Jayasundara *et al.,* 2016; Mekonnen and Hoekstra, 2011). Both studies only included nitrogen as a source of pollution. In comparison to the global benchmark (Mekonnen and Hoekstra, 2011), the global water footprint of tea was larger than the generated water footprint value from our study. In contrast to our study, which used local data, estimation of global water footprint in tea using country-average climate data had a larger water consumptive used (Mekonnen and Hoekstra, 2011). The extent of rainfall, higher productivity, and efficient production will increase water productivity, thus generating lower green and blue component values (Hoekstra *et al.,* 2009; Molden *et al.,* 2007).

Other studies indicated that the pesticides exclusion from grey water footprint assessment is responsible for minor contribution of grey water diminished the associated impact. However, in contrast to other studies (Jayasundara *et al.,* 2016; Mekonnen and Hoekstra, 2011), grey water footprint of tea from this study is not minor and contributes to 27% of the total water footprint. This indicates that pesticide inclusion increases the value of generated water footprint. For instance, using Indonesia's average data, the contribution of a grey component to the total water footprint in crop production in Indonesia was relatively low. It mostly contributes less than 6% for each crop (Bulsink *et al.,* 2010). Similarly, Mekonnen and Hoekstra (2011) showed that within the period 1996 – 2005, the allocation of each water footprint component in average global areas for tea production was 82% green, 10% blue, and 8% grey. These were contrast to our finding that showed the ratio was 60% for green, 12% for blue, and 27% for grey.

Table 5. Input for assessing water footprint of pesticides

Pesticide	α	A_F	A_C	A_D	$αA_CA_D$	1- α	$A_CA_DA_F$	PNEC	GWF^1	GWF^2
Deltamethrin	2.5E-08	0	241.1	0.13	0	0.99	0	1.65E-08	0.12	0.012
Permethrin	6.3E-08	0	11.9	0.08	0	0.99	0	1.26E-08	0.01	0.001
Bifenthrin	5.4E-08	-7 E-155	59.3	0.51	0	0.99	-2.18E-153	1.26E-08	0.33	0.035
Thiamethoxam	0.0005	-0.0075	130.4	0.02	0.001	0.99	-2E+01	0.00097	-0.05	-0.005
								Total grey water	0.4	0.043

Note : α(fraction of each pesticide); A_F (attenuation factor); A_C (cultivated area, ha); A_D(pesticide dose, kg/ha); PNEC(predicted no effect pesticides concentration; kg/m^3); GWF1 (grey water footprint m^3/ha); GWF2 (grey water footprint; m^3/ton)

Table 6. The water footprint of tea from the selected countries

Product	Water footprint value (m³/ton)		
	Consumptive water	Assimilative water	Total
Agrabinta, Indonesia[1]	8,540.12		8,540.12
Indonesia[2]	12,395.		12,395
Gambung, Indonesia[3]	2,346.12	839.38	3185.5
Sri Lanka[4]	12,850.34	73	12,923.34
Global average[5]	8,130	726	8,856

Source: [1](Jefferies *et al.,* 2012), [2](Chapagain and Hoekstra, 2007), [3](present study),
[4](Jayasundara *et al.,* 2016), [5](Mekonnen and Hoekstra, 2011)

Our assessment (Table 5) shows that bifenthrin, a pyrethroid, is contributed the greatest to grey water footprint, and therefore, more likely to contaminate surface water than other studied pesticides. Bifenthrin has a comparatively longer half-life and higher toxicity than other pyrethroids or neonicotinoids applied in tea cultivation (USEPA, 2018; Velisek *et al.,* 2009). Moreover, bifenthrin is less adsorb to the soil than deltamethrin and permethrin due to its lower K_{OC} value. Thus bifenthrin has greater potentiality to contaminate surface water through surface runoff (Laskowski, 2002). As shown in Table 5, the mass of pesticides that potentially reach the surface water through runoff represented by αACAD is higher than the fraction of pesticides that leach to the groundwater (represented by 1-αACADAF). Therefore, due to the more hydrophilic character of bifenthrin, it is expected that the contribution of contamination through runoff is greater than those that leached to the water table.

However, in this study, bifenthrin had the greatest application dose and lower attenuation factor that was likely to contribute more to grey water footprint. The attenuation factor was calculated based on each pesticide's degradation rate, the pesticide retardation factor (which represented the delay of the pesticide transport rate compared with water rate), the soil characteristic, and the water daily net recharge of the soil area (Vale *et al.,* 2019). Because the latter two input parameters were similar for each pesticide applied in this study, the two former input parameters were likely to caused the higher grey water footprint for bifenthrin, in addition to application dose. Furthermore, compared to the other pyrethroids and neonicotinoids used in this study, bifenthrin has the most prolonged half-life in the water of 161 days, which was longer than the permethrin (40 days) and deltamethrin (79 days) (DeMars *et al.,* 2021; Laskowski, 2002). The longer half-life and the lowest adsorbtion capability of bifenthrin to the soil make bifenthrin easily contaminates the surface water and threatens its aquatic organisms. This condition is likely to be worsened by the toxicity property of bifenthrin, which exhibits high acute lethal toxicity to the aquatic organisms (Yang *et al.,* 2018). Moreover, the World Health Organization (WHO) has classified bifenthrin in Toxicity Class II as moderately hazardous pesticides (WHO, 2010).

Conversely, deltamethrin and permethrin have higher K_{OC} values than bifenthrin, indicating a higher retardation factor. The higher K_{OC} values were in line with the retardation factor but inversely proportional to the attenuation factor (Vale *et al.,* 2019). The higher K_{OC} and so the retardation factor nullifies the attenuation factor value (Vale *et al.,* 2019), as could be observed for deltamethrin and permethrin. Furthermore, neonicotinoid, as represented by thiamethoxam, had the lowest grey water footprint contribution of all. Thiamethoxam has relatively lower K_{OC} values and retardation factor than pyrethroids, indicating a relatively higher leaching rate than the others. However, lower application dose which was only 0.025 kg/ha coupled with the lowest toxicity, nullifies the grey water footprint value of thiamethoxam.

Our study indicates that the less toxicity and shorter half-life of each insecticide plays important role in minimizing grey water footprint value. The capability of each pesticide to contaminate the water resources can be evaluated using the GUS (Groundwater Ubiquity Score) index proposed by Gustafson (1989). Theoretically, the higher GUS index represented the higher leaching potential.

However, in this study, bifenthrin with a very low GUS index had the greatest grey water footprint indicating the greatest capability to contaminate the surface water. In contrast, thiamethoxam, which classifies as an insecticide with a very high leaching potential (GUS Index 4.02) had a smaller grey water footprint value compared to others. Therefore, due to its capability to easily contaminated the surface water, bifenthrin should be eliminated or substituted by the other insecticides with lower toxicity and shorter degradation half-lives.

Furthermore, ensuring water sustainability from assimilative capacity perspective can be performed by assessing water availability to assimilate the contaminants. According to the obtained grey water value, the water volume needed to assimilate the contaminant generated during tea production was 839.38 m^3. This value was relatively comparable to another (Mekonnen and Hoekstra, 2011). However, the annual rainfall in this study area was relatively high, which was accounted for 2,652 mm/year. This value is equal to 10,475,400 m^3 of water (Brouwer *et al.,* 1985). Therefore, it indicates that every year, the tea plantation received water that was almost four orders of magnitude higher than needed for contaminants assimilation. However, further analysis is required to assess the water sustainability of local water resources involving all agricultural activities, actual runoff, and environmental flow requirements at the study location.

4. Conclusion

Incorporating pesticides and fertilizers into grey water footprint has changed the percentage contribution of grey water footprint to other water footprint components. To ensure water sustainability from an assimilative capacity perspective, the grey water footprint should be reduced by utilizing less toxic and more rapidly degraded insecticides. By taking only rainfall into account, this study reveals that the water availability in the studied area exceeds the value needed for assimilating all generated pesticides and fertilizers during tea production. Still, further analysis is required to assess the real assimilative capacity of the surface water for contaminants by taking tea and other crops production into account.

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