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Original Research

Water Footprint of Local Herbs in Thailand Using the Water Footprint Network Methodology

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ABSTRACT

This study quantified the water footprint (WF) of four economically important Thai medicinal herbs−*Curcuma longa, Kaempferia parviflora, Andrographis paniculata* and *Momordica charantia*−using the Water Footprint Network (WFN) methodology together with Thailand-specific climatic and cultivation data. The assessment covered green, blue, and gray WF components and incorporated basin-level water scarcity characterization. The results show that *Curcuma longa* had the lowest total WF (535 m^3/ton), driven primarily by green water use, while *Momordica charantia* had the highest WF (2,152 m^3/ton), reflecting substantial blue and gray water requirements. *Kaempferia parviflora* and *Andrographis paniculata* presented intermediate WFs of 1,088 and 1,869 m^3/ton, respectively. Spatial analysis revealed strong provincial variability linked to rainfall patterns and irrigation demand, particularly for *Momordica charantia* in northern and lower-central regions. Sensitivity analysis identified crop evapotranspiration and the leaching-runoff fraction as the most influential parameters across all herbs. The findings provide a robust evidence based for optimizing irrigation practices and guiding sustainable water management strategies within Thailand's herbal cultivation sector.

1. INTRODUCTION

The water footprint (WF) has become a fundamental indicator for evaluating the sustainability of agricultural production systems, providing a quantitative measure of freshwater consumed or polluted within a product's system boundary (Hoekstra and Mekonnen, 2012). Defined across three components−green, blue, and gray−the WF framework offers a comprehensive understanding of crop-specific water use, including soil moisture reliance, irrigation demand, and water required for assimilating nutrient pollutions (Hoekstra et al. 2011). The concept, formalized by Hoekstra and Mekonnen (Hoekstra et al. 2011, Hoekstra and Mekonnen, 2012), has since been widely applied across regions and crop types, contributing to improved water-use planning, agricultural benchmarking, and environmental policy development (Mekonnen and Hoekstra, 2011, Mekonnen and Hoekstra, 2014, Lovarelli et al. 2016). Numerous global studies demonstrate that irrigation-intensive crops tend to exert disproportionately high blue WF, intensifying water scarcity in hydrologically stressed regions (Mekonnen and Hoekstra, 2014). Evidence from arid and semiarid countries further supports this trend, highlighting that cereal and horticultural crops are particularly sensitive to irrigation dependency and blue-water vulnerability (Mekonnen and Hoekstra, 2020).

Thailand plays an increasingly important role in the global herbal medicine market, with more than 1,800 plant species recorded for medicinal purposes and over 200 commercially cultivated nationwide (Department of Thai Traditional and Alternative Medicine, 2023). National strategies under the Ministry of Public Health have designed several species as “herbal champion products” to strengthen domestic competitiveness and export capacity (Department of Thai Traditional and Alternative Medicine, 2023). Among these, *Curcuma longa, Kaempferia parviflora, Andrographis paniculata* and *Momordica charantia* stand out due to their pharma ecological properties, rising consumer demand, and expanding production areas (Ngamsomjit, 2008). Despite their growing economic importance, systematic evaluations of their water-use requirements and associated environmental pressures are still limited, resulting in a substantial knowledge gap regarding their water consumption patterns across different agroecological contexts.

Existing WF studies in Thailand have largely focused on staple and industrial crops. For instance, rice has been extensively analyzed, with its WF inventory informing national water policy, food labeling, and sustainability assessments (Mungkung et al. 2019). Cassava research has revealed high blue-water demand in the northeastern region, where prolonged dry seasons create chronic water stress (Kaewjampa et al. 2016). Sugarcane studies have documented irrigation-efficiency gaps in eastern provinces (Chaibandit et al. 2017), while investigations of palm oil plantations and coffee production highlight strong regional variations in water use driven by climatic and soil differences (Suttayakul et al. 2016, Ratchawat et al. 2020). These studies collectively establish valuable benchmarks for Thailand’s major crops; however, medicinal herbs remain underexamined, particularly in terms of their spatial water-use dynamics and implications for water resource management. This absence of herb-specific WF benchmarks limits the ability of policymakers and producers to design effective irrigation strategies and evaluation potential risks related to water scarcity.

The selection of the four herbs examined in this study reflects both their economic relevance and their contrasting agroecological characteristics. *Curcuma longa* and *Kaempferia parviflora* are predominantly cultivated in northern and northeastern provinces, where rainfall is more dependable and rain-fed agriculture is common, suggesting stronger reliance on green water (Ngamsomjit, 2008). In contrast, *Andrographis paniculata* and *Momordica charantia* are primarily grown in the central region, where developed irrigation systems support intensive horticultural production, implying higher blue water dependency (Gheewala et al. 2014). This geographic differentiation provides an opportunity to compare water-use patterns across distinct climatic zones and to identify potential hotspots where irrigation pressure may be particularly high.

Given the increasing significance of medicinal herbs in Thailand's agricultural economy and the limited WF data available for these crops, this study aimed to quantify and compare the green, blue, and gray WFs of four selected species using the WFN methodology. The objectives are threefold: (1) to determine the relative contributions of each WF component at the provincial and national scales; (2) to benchmark the water intensity of medicinal herbs against commonly studied staple and industrial crop-specific water use data with regional water scarcity indicator (WSI), this study provides an evidence-based foundation for improving irrigation efficiency, strengthening water-resource planning, and supporting sustainable agricultural development of Thailand's medicinal herb sector.

2. MATERIALS AND METHODS

2.1 Goal and Scope Definition

The primary goal of this study was to quantify and compare the green, blue, and gray WF's of four economically important Thai medicinal herbs: *Curcuma longa, Kaempferia parviflora, Andrographis paniculata* and *Momordica charantia*. These species were selected based on their official designation as "herbal champion products" by the Thai Ministry of Public Health, reflecting their economic value and market relevance (Department of Thai Traditional and Alternative Medicine, 2023). The provinces included in the analysis were identified according to the largest cultivation area and production volumes reported in national agricultural statistics, ensuring representation of major producing regions and capturing geographic variability. Provincial WF results were subsequently aggregated to the national averages using a mass-balance approach that integrates provincial crop water use and harvested production.

The functional unit (FU) was defined as one ton of harvested fresh product, a widely used in WF studies due to its practical interpretability for producers, traders, and policymakers (Mekonnen and Hoekstra, 2011, Hoekstra and Mekonnen 2012). Although FUs based on dry matter or active compounds (e.g. milligrams of curcumin) can provide more pharmaceutical-oriented insights, the fresh-weight FU was selected to maintain consistency with existing WF benchmarks for staple and industrial crops (Mekonnen and Hoekstra, 2014). The system boundary was restricted to the cultivation stage, covering consumptive water use (evapotranspiration) and nutrient-related pollution (leaching and runoff) from planting to harvest (Hoekstra et al. 2011). Downstream processes−including transportation, processing, and packaging−were excluded to maintain focus on agricultural water management in alignment with the WFN methodology (Hoekstra et al. 2011).

2.2 Water Footprint Accounting Framework

The analysis followed the WFN assessment manual (Hoekstra et al. 2011), which is widely recognized as the global reference framework for volumetric water accounting. This approach has been applied to a broad range of crops–including cereals, oil crops, and horticultural species–and is considered robust for spatially explicit analyses across diverse agroecological conditions (Gheewala et al. 2014, Mekonnen and Hoekstra, 2014). The volumetric method is particularly suitable for Thailand, where climatic heterogeneity and variations in irrigation infrastructure strongly influence consumptive water use.

The green and blue components of the WF were calculated using Eq. (1) and Eq. (2):

$$WF_{green} = \frac{CWU_{green}}{Y} \qquad \ldots(1)$$

$$WF_{blue} = \frac{CWU_{blue}}{Y} \qquad \ldots(2)$$

Where CWU is the crop water use (m^3/ha), and Y is the crop yield (ton/ha). CWU was estimated using CROPWAT8.0, a software tool developed by the Food and Agriculture Organization (FAO), which applies the Penman-Monteith model to calculate reference evapotranspiration (ET_0). This model is internationally regarded as the most physically consistent and transferable approach for estimating evapotranspiration (Allen et al. 1998). Crop coefficients (K_c) were use to adjust ET_0 for species-specific characteristics.

The gray WF, representing the volume of freshwater required to assimilate leached nitrogen, was calculated using Eq. (3):

$$WF_{gray} = \frac{\propto \times AR}{(C_{max} - C_{nat}) \times Y} \qquad \ldots(3)$$

Where AR is the nitrogen application rate (kg/ha), $\propto$ is the leaching-runoff fraction, C_{max} is the maximum acceptable nitrate concentration, and C_{nat} is the natural background concentration in the receiving body. Following assumption commonly adopted in WF studies (Mekonnen and Hoekstra, 2014, Lovarelli et al. 2016). $\propto$ was fixed at 10%, C_{nat} was assumed to be zero and C_{max} was set at 10 mg NO_3-N/L based on WHO water-quality guidelines. Although these assumptions were widely used, they were explicitly acknowledged as a source of uncertainty in the analysis.

Provincial water footprint results were aggregated to derive national average values using a mass-balance approach based on harvested cultivation area and production. National component-specific WF values were calculated as Eq. (4):

$$WF_{c,national} = \frac{\sum_i (CWU_{c,i} \times A_i)}{\sum_i (Y_i \times A_i)} \qquad \ldots(4)$$

Where $CWU_{c,i}$ represents the crop water use (green, blue, or gray component) in province i, Y_i denotes provincial yield, and A_i denotes harvested cultivation area. This approach ensures that national WF values reflect total water consumption divided by total production rather than a simple arithmetic average of provincial ratios.

2.3 Data Sources and Parameters

Climatic data on rainfall, temperature, humidity and wind speed were obtained from the Thai Meteorological Department. Agricultural statistics—including cultivation area, yield, and fertilizer input—were sourced from the Department of Agricultural Extension (Chanakanachai and Lekunwong, 2000). Crop coefficients (K_c) were derived from published lysimeter-based measurements and established datasets. For *Curcuma longa*, *Kaempferia parviflora* and *Andrographis paniculata*, representative K_c values calibrated against the Penman-Monteith method were adopted from Ngamsomjit (2008). For *Momordica charantia*, species-specific lysimeter measurements were unavailable. Therefore, a representative mid-season crop coefficient (Kc = 1.15) from FAO for cucumber cultivated under full canopy conditions was adopted as a proxy (Allen et al., 1998). This substitution was applied to maintain parameter consistency in the absence of species-specific experimental data.~~.~~ To enhance reproducibility, the representative Kc values applied in the model and their corresponding sources are summarized in Table 1. The uncertainty associated with literature-derived Kc values was addressed through ± 10% perturbation in the sensitivity analysis.

Nitrogen application rates were derived from standardized cultivation guidelines issued by the Department of Agricultural Extension (Chanakanachai and Lekunwong, 2000). A single crop-specific AR was applied uniformly across all provinces to maintain methodological consistency within the comparative water footprint assessment framework. The influence of potential uncertainty associated with nitrogen inputs was evaluated through ± 10% perturbation in the sensitivity analysis.

Table 1: Representative crop coefficients (Kc) applied in CROPWAT calculations.

Herb	Kc used in model	Basis/note	Source
Kaempferia parviflora	1.19	Lysimeter-based; Penman-Monteith calibrated	Ngamsomjit (2008)
Curmuma longa	1.12	Lysimeter-based; Penman-Monteith calibrated	Ngamsomjit (2008)
Andrographis paniculata	1.77	Lysimeter-based; Penman-Monteith calibrated	Ngamsomjit (2008)
Momordica charantia	1.15	Proxy using cucumber mid-season K_c under full canopy conditions	Allen et al. (1998)

2.4 Water Scarcity Assessment

To contextualize irrigation dependence, blue WF values were compared with the blue WSI of Thailand's 25 river basins, obtained from the national assessment by Gheewala et al. (Gheewala et al. 2014). Although the dataset was published in 2014, it remains the most comprehensive and spatially detailed national reference available. The WSI represents the ratio of blue-water consumption to renewable blue-water availability, and therefore serves as a proxy for the degree of water stress within each basin (Mekonnen and Hoekstra, 2020).

Integrating blue WF with basin-level WSI enables the identification of areas where irrigation-intensive crops pose heightened risks of local water competition. This paired assessment provides not only a measure of consumptive water use but also its contextual scarcity, offering clearer implications for sustainability planning and policy development. The combined WF-WSI framework is consistent with emerging approaches in water-resource analysis that emphasize both volumetric demand and local hydrological constraints.

2.5 Methodological Assumptions and Limitations

Several assumptions are embedded in this methodology. First, fertilizer input rates from agricultural statistics primarily reflect commercial systems, possibly underestimating smallholder or informal cultivation practices, where efficiency is lower. Second, the exclusion of downstream processes, such as drying and processing, implied that the results are conservative estimates of the total product footprints. These limitations overlap with those discussed in Discussion section, where they are revisited along with recommendations for future work.

2.6 Sensitivity Analysis Framework

A sensitivity analysis was conducted to evaluate the robustness of the WF results and to quantify the relative influence of key parameters on the green, blue, and gray components. Each selected variable was independently perturbed by ±10% or ±20% around its baseline value while all others parameters were held constant. This one-at-a-time approach follows the standard practices widely applied in agricultural WF assessments and is recommended in the WFN methodology (Hoekstra et al. 2011). The tested parameters represent both climatic-agronomic drivers and management-related factors that influence water consumption and pollutant assimilation.

For the climatic-agronomic group, K_c and ET_0 were varied by ±10%, reflecting the measurement and modeling uncertainty range suggested in FAO guidelines (Allen et al. 1998). Crop yield (Y) was also varied by ±10%, consistent with the typical inter-annual variability reported in the national agricultural statistics (Ngamsomjit, 2008). Because yield is the denominator in the calculation of all WF components, small changes in Y can induce disproportionally large fluctuations in the total WF, especially in provinces where productivity is comparatively low.

For management-related factors, the AR and ∝ were varied by ±20% to reflected the broader empirical uncertainties associated with fertilization practices and soil-water interactions, as reported in review studies (Mekonnen and Hoekstra, 2014, Mungkung et al. 2019). In the baseline scenario, ∝ was fixed at 0.1, following the WFN manual (Hoekstra et al. 2011), but its ±20% perturbation captures the spatial variability documented in field-scale experiments (Lovarelli et al. 2016). This approach allows the analysis to incorporate both biophysical uncertainty and management variability, ensuring a more realistic assessment of potential deviations in WF estimates.

The configuration of the sensitivity tests is summarized in Table 2, which specifies the parameter descriptions, applied perturbation ranges, and supporting rationale.

Table 2: Sensitivity test matrix for parameters affecting green, blue, and gray WF components.

Parameter	Description	Variation (Δ%)	Rationale and Source
Crop yield (Y)	Output per unit area; affects all WF components inversely	±10%	Field yield uncertainty; range adopted from WFN (Hoekstra and Mekonnen, 2012; Mekonnen and Hoekstra, 2014)
ET_0/K_c	Reference evapotranspiration and crop coefficient; affect green and blue WF components	±10%	Reflects meteorological and phenological variability (Hoekstra and Mekonnen, 2012)
Application rate (AR)	Nitrogen fertilizer application; affects gray WF	±20%	Field survey
Pollutant assimilation factor (∝)	Maximum allowable N concentration in receiving water bodies	±20%	(Allen et al. 1998; Hoekstra and Mekonnen, 2012)

3. RESULTS

3.1. Average Water Footprint of Medicinal Herbs

Provincial-level analysis revealed substantial variability in the WF profiles of the four economically strategic Thai medicinal herbs (Table 3). *Curcuma longa* consistently exhibited the lowest total WF, averaging 535 m^3/ton. This comparatively favorable performance is largely attributable to its strong reliance on green water, which accounted for more than 40% of its total WF. In contrast, *Kaempferia parviflora* demonstrated a considerably higher total WF 1,088 m^3/ton, driven primarily by irrigation demand; the blue component contributed more than 40% of the total footprint, underscoring its sensitivity to water availability and basin-level scarcity conditions.

Table 3: National average WF of four economically strategic Thai medicinal herbs.

Herb	Green WF		Blue WF		Gray WF		Total WF
	(m^3/ton)	%	(m^3/ton)	%	(m^3/ton)	%	(m^3/ton)

Curcuma longa	232	43.4	157	29.3	146	27.3	535
Kaempferia parviflora	292	26.8	451	41.5	345	31.7	1,088
Andrographis paniculata	208	11.1	1,463	78.3	198	10.6	1,869
Momordica charantia	174	8.1	1,686	78.3	292	13.6	2,152

More pronounced contrasts were observed between *Andrographis paniculata* and *Momordica charantia.* The total WF of *Andrographis paniculata* averaged 1,869 m^3/ton, with nearly 80% originating from blue water. This heavy reliance on irrigation reflects the crop's concentration in Thailand's Central region, where intensive agriculture and well-developed irrigation systems dominate production landscapes (Gheewala et al. 2014). *Momordica charantia* exhibited the highest total WF at 2,152 m^3/ton—nearly four times greater than *Curcuma longa*—reinforcing the established principle that lower crop productivity is strongly associated with disproportionately high water intensities (Abadaei and Etedali, 2017).

At the national scale, a consistent pattern emerged: blue WF dominated the total WF for most medicinal herbs, indicating substantial irrigation dependence. Although smaller in magnitude, the gray WF remained a non-negligible component, especially for *Momordica charantia*, where relatively high AR resulted in elevated nutrient-assimilation water requirements. Nitrogen inputs in this study were derived from standardized sysnthetic fertilizer recommendations issued by Chanakanachai, W. and Lekunwong, S. (2000), and uniform crop-specific AR were applied consistently across provinces. Because gray WF is directly proportional to AR and inversely proportional to yield (Y), relatively high fertilizer intensity combinaed with moderate yield levels contributed to elevated gray WF shares for certain herbs, particularly *Kaempferia parviflora*. It should be noted that the gray WF represents the theoretical freshwater volume required to dilute leached nitrogen to acceptable concentration thresholds under the WFN framework. This indicator reflects potential nutrient pressure under conventional fertilizer management practices rather than direct exceedance of basin-level water quality standards.

These combined results indicate that selected medicinal herbs are considerably more water-intensive than staple crops such as rice (1,665 m^3/ton) (Mungkung et al. 2019), and vastly exceed the water-use efficiency of industrial crops such as sugarcane (178 m^3/ton) (Chaibandit et al. 2017).

From a policy perspective, optimizing nitrogen application through precision fertilization, soil testing, and improved nutrient management practices could reduce the gray WF without compromising productivity. Integrating nutrient management with irrigation planning would be particularly important in provinces where fertilizer intensity and irrigation dependence overlap. The comparative patterns across herbs highlight the need for spatially explicit WF assessments. While *Curcuma longa* may be considered relatively more sustainable due to its strong dependence on *rainfall, Momordica charantia* and *Andrographis paniculata* illustrate the challenges associated with irrigation-intensive cultivation in regions already vulnerable to water scarcity. These findings underscore the importance of integrating crop selection, irrigation management, and spatial planning into strategies aimed at improving agricultural water-use efficiency in Thailand.

3.2. Spatial Variability of Water Footprints

The spatial distribution of WFs across provinces revealed distinct patterns for the four medicinal herbs. *Curcuma longa* is predominantly cultivated in northern provinces such as Chiang Mai, where rainfall reliably supports production. As a result, green WF contributes approximately 50% of the total footprint in most locations, confirming the crop's relatively low dependence on irrigation. Nevertheless, certain provinces-most notably Phrae-displayed exceptionally high blue WF values (2,802.2 m^3/ton), indicating localized irrigation intensities that diverge markedly from the broader rain-fed production pattern.

In contrast, *Kaempferia parviflora* exhibited strong irrigation dependence in northeastern provinces. Khon Kaen recorded blue WF levels exceeding 2,000 m^3/ton, whereas Phetchabun showed considerably lower levels at 403.4 m^3/ton. These spatial contrasts highlight the influence of agroecological and hydrological conditions on water-use patterns (Li et al. 2022). Provinces experiencing water-stressed conditions (e.g. Nakhon Ratchasima, WSI = 0.927) demonstrated heightened vulnerability when high irrigation demand coincided with already scarce water resources.

The distributions of *Andrographis paniculata* and *Momordica charantia* were more geographically restricted, yet they exhibited significantly higher WF intensities. In Ratchaburi, both crops reached extreme total WF values-4,509.3 m^3/ton for *Andrographis paniculata* and 4,318.6 m^3/ton for *Momordica charantia*. These values are several times higher than their respective national averages and were driven primarily by blue WF contributions exceeding 75%. These findings underscore Ratchaburi as a critical hotspot for irrigation intensive medicinal herb cultivation. Because blue WF is expressed per unit of production (m^3/ton), lower productivity mathematically amplifies per-ton water footprint values even when irrigation water use remains within typical agronomic ranges. This yield-driven mechanism explains the apparent outliers observed in the provincial distribution and highlights the importance of interpreting WF intensities in conjunction with productivity metrics.

Overall, the spatial analysis confirmed that herbs grown in predominantly rain-fed regions (e.g., *Curcuma longa* in northern provinces) exhibit more balanced WF profiles, with substantial contributions from green water. Conversely, crops cultivated in irrigated Central and Northeastern provinces-particularly *Andrographis paniculata* and *Momordica charantia* are characterized by disproportionately high blue WF dependencies. Provinces such as Phrae, Khon Kaen, and Ratchaburi thus emerge as water-intensive cultivation zones, emphasizing the need for targeted, region-specific water-use strategies in the context of Thailand's increasing water scarcity challenges.

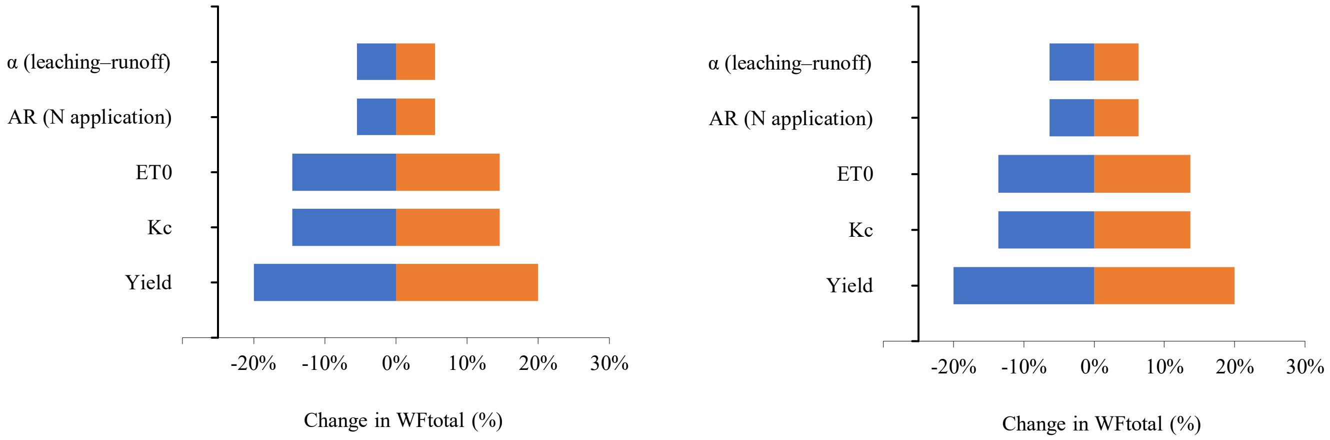
3.3. Sensitivity and Uncertainty Analysis

The sensitivity analysis evaluated the influence of key parameters on total WF using a proportional approach consistent with the WFN accounting structure and the FAO evapotranspiration formulation. Yield was treated as the common denominator for all WF components; therefore, a ±10-20% change in yield translated directly into an equivalent ±10-20% change in total WF. The K_c and ET_0 were assumed to influence both green and blue WF through their effects on crop water use. Consequently, the magnitude of their influence on total WF was proportional to the combined share of green and blue components. In contrast, AR and $\propto$ were assumed to affect only the gray component, and their influence on total WF was proportional to the gray WF share. Component shares for each herb were computed and summarized in Table 2.

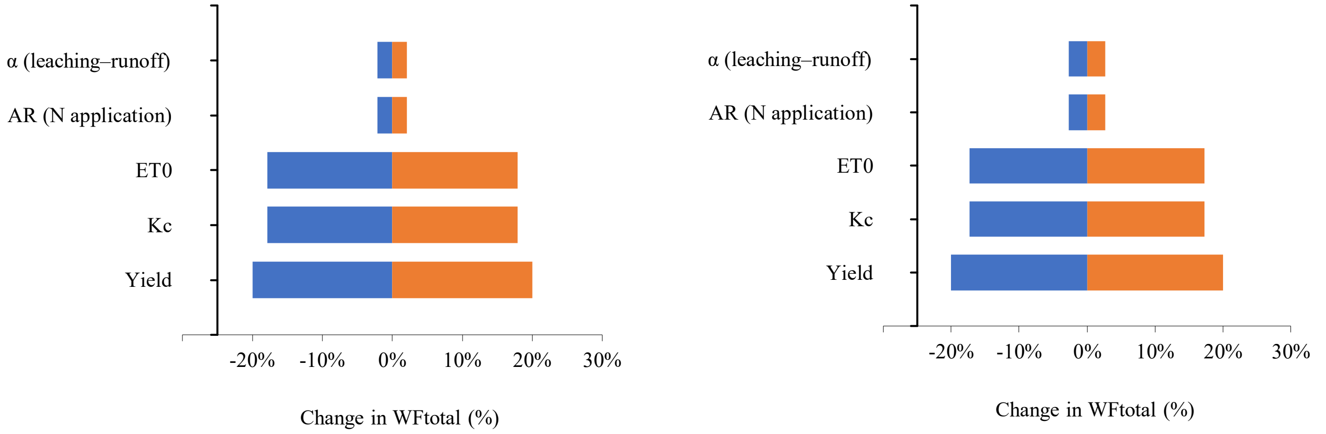
Figure 1 presents the results in tornado-style panels for each herb. Yield consistently dominated the sensitivity profile across all species due to its inverse functional relationship with the water-use intensity, producing a one-to-one proportional response. K_c and ET_0 represented the second most influential group of parameters, particularly for *Andrographis paniculata* and *Momordica charantia*, where the combined green and blue shared approached 0.89 and 0.86, respectively. Under a ±20% perturbation, these shares translated into total WF shifts of approximately ±17.9% for *Andrographis paniculata* and ±17.3% for *Momordica charantia*. In contrast, *Curcuma longa* and *Kaempferia parviflora* exhibited lower, though still meaningful, sensitivity to K_c and ET_0, due their lower combined green and blue proportions.

Parameters affecting the gray WF component exerted comparatively smaller influences on total WF because the gray shares were modest for three of the four herbs. The strongest gray-related sensitivity was observed for *Kaempferia parviflora*, where the gray share of approximately 0.32 resulted in a ±6.3% change in total WF under a ±20% perturbation. This pattern highlights the limited role of nutrient-related processes in shaping overall WF variability relative to the dominant effect of irrigation water use.

These results have two practical implications for policymakers. First, interventions that enhance yield, such as agronomic improvements and better planting materials, are likely to deliver the largest proportional reductions in WF per ton across all 4 herbs. Second, for species whose WF is strongly governed by the green and blue components, especially *Andrographis paniculata* and *Momordica charantia*, climate- and management-sensitive parameters (K_c and ET_0) warrant careful calibration and local validation to minimize model uncertainty and to prioritize water-saving strategies. In contrast, reductions in nitrogen application or improved nutrient management would generate relatively smaller changes in total WF at the national mean level, although local effects may be stronger where the gray share is high.



(a) *Curcuma longa* (b) *Kaempferia parviflora*



(c) *Andrographis paniculata* (d) *Momordica charantia*

Fig. 1: Percentage change in total WF under parameter variation for: (a) *Curcuma longa*, (b) *Kaempferia parviflora*, (c) *Andrographis paniculata*, and (d) *Momordica charantia*

4. DISCUSSION

4.1 Interpretation and Benchmarking of Water Footprint Results

Building upon the provincial-level results in Table 3, the total WF of the four medicinal herbs exhibited substantial variation across provinces as well as benchmarked against Thailand's major food and industrial crops. *Curcuma longa* recorded the lowest total WF (535 m^3/ton), followed by *Kaempferia parviflora* (1,088 m^3/ton), *Andrographis paniculata* (1,869 m^3/ton), and *Momordica charantia* (2,152 m^3/ton). This fourfold range is primarily shaped by differences in irrigation dependence and yield performance, with irrigation-intensive species generally exhibiting higher total WF values.

When compared with staple and industrial benchmarks, the total WF of *Curcuma longa* was markedly lower than that of rice (1,665 m^3/ton) (Mungkung et al. 2019), although still approximately three times greater than that of sugarcane (178 m^3/ton) (Chaibandit et al. 2017). Conversely, *Andrographis paniculata* and *Momordica charantia* displayed total WFs approaching that of cassava (2,500 m^3/ton in Northeast Thailand)

(Kaewjampa et al. 2016), indicating irrigation intensities comparable to Thailand's high-input industrial crops. These contrasts highlight the diverse water-use efficiencies of medicinal herbs and emphasize the need to differentiate species-specific water management strategies.

The provincial distribution of total WF (Figure 2) demonstrated clear regional variability. Northern provinces, such as Chiang Mai and Nan exhibited strong green-water dominance due to reliable monsoonal rainfall and limited reliance on irrigation (Ngamsomjit, 2008). In contrast, Central provinces-including Ratchaburi and Nakhon Pathom-recorded blue-water shares exceeding 70% for *Andrographis paniculata* and *Momordica charantia*. These patterns overlapped with moderate to high basin-level water scarcity (WSI = 0.25-0.3) (Mekonnen and Hoekstra, 2020, Gheewala et al. 2014), signaling heightened vulnerability where irrigation demand coincides with constrained freshwater availability.

Gray WF contributions were generally smaller but remained important in specific locations. For example, elevated gray WF values for *Andrographis paniculata* in Nakhon Pathom (1,100 m^3/ton) reflected nitrogen leaching levels comparable to those documented in sugarcane systems (Chaibandit et al. 2017, Suttayakul et al. 2016, Gheewala et al. 2014). This finding underscores the need for site-specific nutrient management to mitigate nonpoint-source pollution in regions with high fertilizer application rates.

Overall, the results demonstrate that medicinal herbs should not be viewed as uniformly low-impact crops. Their water-use efficiency depends heavily on biophysical and managerial factors-particularly yield performance and irrigation intensity. Improving irrigation scheduling, enhancing soil moisture retention, and increasing on-farm rainwater harvesting could substantially reduce total WF in irrigation-dependent provinces. Likewise, promoting high-yield varieties and implementing crop zoning aligned with basin-level water availability would support the sustainable expansion of Thailand's medicinal herb sector, consistent with the goals of the national Bio-Circular-Green policy framework (Ministry of Higher Education Science Research and Innovation, 2019).

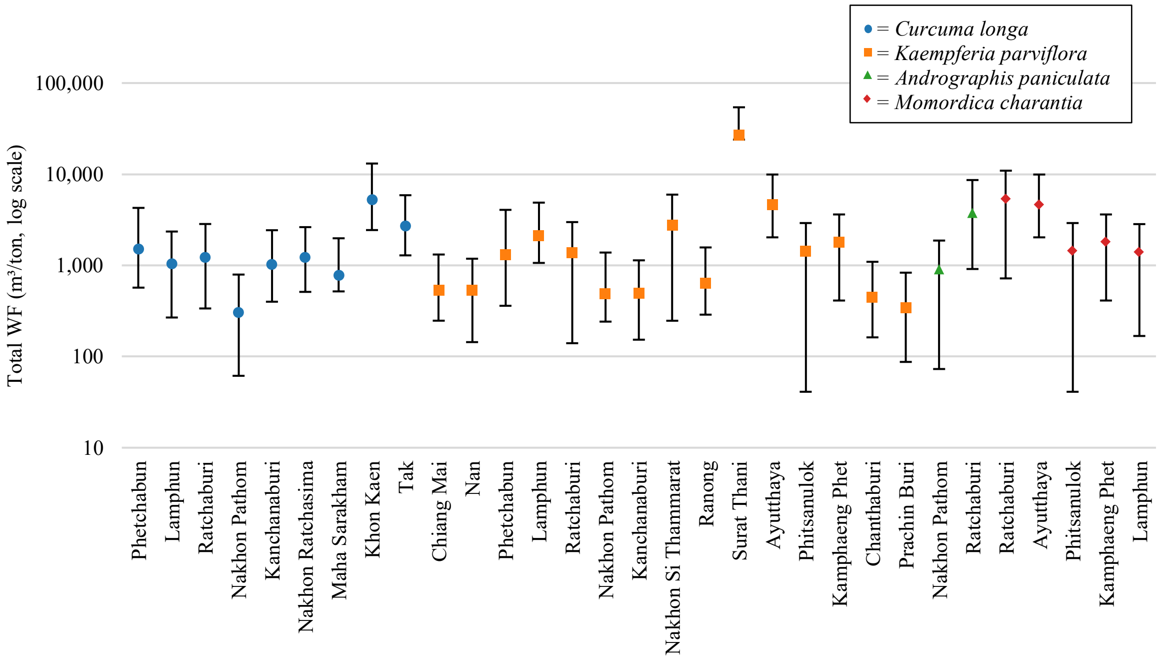


Fig. 2: Provincial distribution of total WF of 4 four medicinal herbs.

Note: Vertical lines represent provincial range (min-max), and markers indicate cultivation-area-weighted average values.

4.2 Comparative Evaluation of Water Footprint Components

A comparative appraisal of the component shares revealed clear differences in hydrological dependence among the four medicinal herbs. *Curcuma longa* exhibited a predominance of green water, reflecting substantial reliance on effective rainfall and comparatively limited irrigation substitution under typical cultivation practices. This pattern aligns with the WFN accounting construct, in which green WF traces crop evapotranspiration sourced from precipitation stored in the root zone (Mekonnen and Hoekstra, 2011). In contrast, *Kaempferia parviflora* showed a moderate blue-water reliance (42%), whereas *Andrographis paniculata* and *Momordica charantia* were strongly blue-dominant with blue fractions exceeding 75%. Global benchmarking literature consistently demonstrates that irrigation-intensive cropping systems tend to elevate blue WF, particularly in regions with pronounced rainfall deficits or erratic seasonal precipitation (Mekonnen and Hoekstra, 2014).

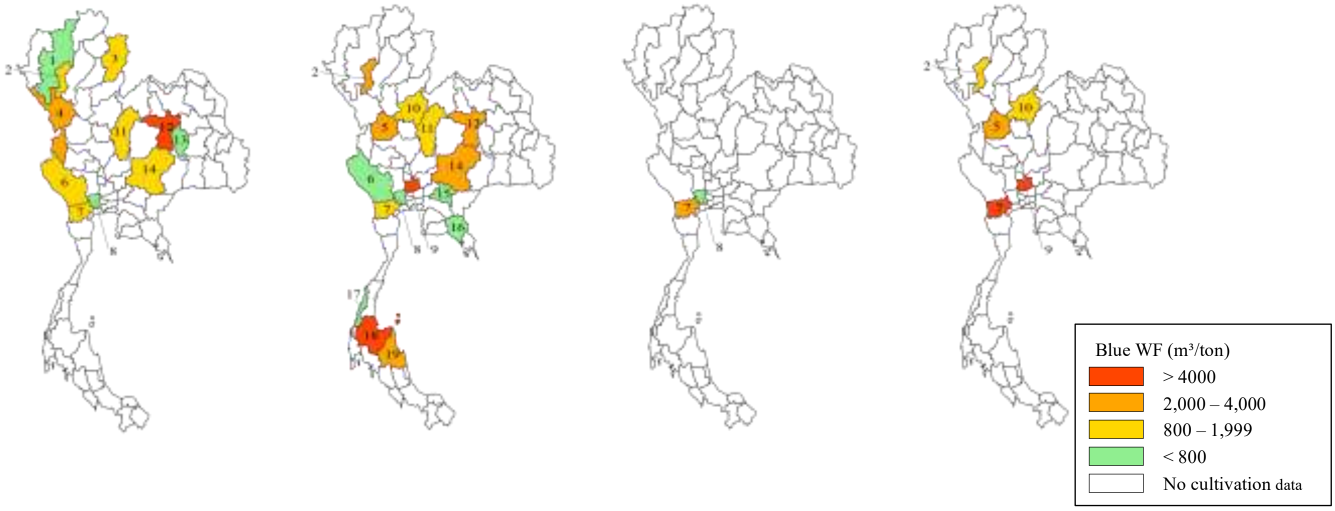
When the component shares are interpreted against national crop benchmarks, the magnitude of blue-water reliance among the herbs becomes more evident. The relatively high green-water share of *Curcuma longa* is biophysically plausible because C3 crops typically exhibit lower intrinsic water-use efficiency than C4 crops such as sugarcane (Chaibandit et al. 2017). Correspondingly, the high total and blue footprints of *Andrographis paniculata* and *Momordica charantia* align with the well-established inverse relationship between the unit WF and agricultural productivity; lower yields inflate volumetric footprints when evapotranspiration is broadly similar across species (Lovarelli et al. 2016). These comparative signals indicate that agronomic interventions that agronomic interventions that increase yield per unit-area-while keeping crop water use relatively stable-offer a direct and effective lever to reduce unit WF without requiring geographic shifts in production (Lovarelli et al. 2016).

The component profiles also imply distinct management priorities. For *Curcuma longa*, where green water dominates, improvements in soil moisture retention and rainwater management could yield substantial efficiency gains. Practices such as residue retention, mulching, and enhanced infiltration can stabilize the effective use of precipitation and reduce the need for supplemental irrigation (Mekonnen and Hoekstra, 2014). For blue-dominated herbs, field-level irrigation efficiency becomes central. Opportunities include improved irrigation scheduling based on crop evapotranspiration, adoption of water-saving delivery systems, and monitoring tools that minimize abstraction from blue sources (Mekonnen and Hoekstra, 2020). In practice, component-aware strategies are complementary: enhancing green-water capture reduces irrigation demand, while precise irrigation improves the productivity of each cubic meter abstracted from blue sources (Mekonnen and Hoekstra, 2014).

Positioning these findings within Thailand's broader evidence base highlights the importance of component-specific benchmarking. Previous national studies have documented substantial blue-water use in intensively managed crop systems and have recommended allocation frameworks that account for basin-level scarcity when promoting high-value agriculture expansion (Gheewala et al. 2014). The present comparative assessment shows that medicinal herbs differ markedly in their green-blue balances, indicating that uniform policy guidance is unlikely to be effective. Rather, crop-specific, and component-specific performance targets-supported by agronomic improvements and basin-aware siting-provide a more credible pathway to lowering unit WF while maintaining market supply (Mekonnen and Hoekstra, 2014).

4.3 Provincial Analysis of Blue WF and its Relationship with Water Scarcity

The spatial distribution of blue WF among the four medicinal herbs revealed distinct irrigation-dependency patterns (Figure 3a-3d). When blue WF values were overlaid with the WSI of Thailand's 25 river basins, clear hotspots emerged where cultivation coincided with medium-to-high water-stress zones. These findings align with previous evaluations by Hoekstra and Mekonnen (Hoekstra and Mekonnen, 2012) and Mekonnen and Hoekstra (Mekonnen and Hoekstra, 2011) and align with the national-scale assessment of Gheewala et al. (Gheewala et al. 2014). Collectively, these studies demonstrate that geographic placement and irrigation strategy strongly govern water-use efficiency in Thailand's agricultural systems.



(a) *Curcuma longa* (b) *Kaempferia parviflora* (c) *Andrographis paniculata* (d) *Momordica charantia*

1-Chiang Mai
2-Lamphun
3-Nan
4-Tak
5-Kamphaeng Phet
6-Kanchanaburi
7-Ratchaburi
8-Nakhon Pathom
9-Ayutthaya
10-Phitsanulok
11-Phetchabun
12-Khon Kaen
13-Maha Sarakham
14-Nakhon Ratchasima
15-Prachin Buri
16-Chanthaburi
17-Ranong
18-Surat Thani
19-Nakhon Si Thammarat

Fig. 3: Provincial distribution of blue WF (m^3/ton) for: (a) *Curcuma longa*, (b) *Kaempferia parviflora*, (c) *Andrographis paniculata*, and (d) *Momordica charantia*.

For *Curcuma longa*, blue WF remained relatively low across most Northern provinces (≤ 400 m^3/ton), reflecting predominantly rain-fed production. However, in the Chao Phraya Basin-particularly Nakhon Pathom and Suphan Buri-blue WF exceeded 100 m^3/ton in areas already experiencing moderate water stress (WSI ≈ 0.25-0.30) (Gheewala et al. 2014). This suggests that even for a relatively water-efficiency crop such as *Curcuma longa*, expansion into irrigation zones may heighten local water scarcity pressures.

Kaempferia parviflora exhibited markedly higher blue WF values (> 1,000 m^3/ton), with hotspots in Khon Kaen and Nakhon Ratchasima located within the Mun-Chi Basin, where WSI ranged from 0.47 to 0.93 (Gheewala et al., 2014). These findings reflect the high irrigation dependence of *Kaempferia parviflora* cultivation and its potential to intensify water competition in drought-prone environments. Similar blue-water pressures have been documented for cassava and sugarcane grown in Northeastern Thailand (Kaewjampa et al. 2016), as well as intensively irrigated sugarcane systems in Eastern Thailand (Chaibandit et al. 2017). Regional hydrological studies also show that such irrigation intensities can amplify seasonal water shortages during dry years (Chanakanachai and Lekunwong, 2000).

For *Andrographis paniculata*, blue WF constituted more than 70% of the total footprint across Central Thailand. Ratchaburi recorded extreme values exceeding 4,000 m^3/ton, even though the Mae Klong Basin exhibits a relatively low WSI (≈ 0.018) (Gheewala et al. 2014). Such elevated blue WF under low scarcity conditions suggests opportunities for on-farm water- use efficiency improvements, such as surface-irrigation modernization or improved recycling. By contrast, Nakhon Pathom combines a moderate WSI (≈ 0.29) with blue WF above 1,100 m^3/ton, making it a priority zone for irrigation optimization and the adoption of water-saving systems (Allen et al. 1998).

Provincial blue WF values for *Momordica charantia* reached up to 2,500 m^3/ton in hotspots such as Ratchaburi and Ayutthaya, coinciding with moderate-to-high WSI values (0.02–0.34). These patterns align with global analyses by Mekonnen and Hoekstra (Mekonnen and Hoekstra, 2011, Mekonnen and Hoekstra, 2020), which emphasize that irrigated horticultural crops can generate localized water competition even in moderately stressed basins. The concurrence between high blue WF and water scarcity suggests that *Momordica charantia* is particularly sensitive to basin-level hydrological constraints.

To further clarify these relationships, provincial blue WF values were plotted against basin-level WSI (Figure 4). Rather than a single linear response, the data revealed heterogeneous clusters driven by crop type and location. Provinces combining medium-to-high WSI with elevated blue WF—such as Nakhon Pathom and Khon Kaen—represent priority hotspots for risk management in irrigated herb production (Gheewala et al. 2014). Conversely, Ratchaburi in the Mae Klong Basin (WSI ≈ 0.018) displayed high blue WF despite low scarcity conditions, indicating substantial room for efficiency improvement rather than systemic scarcity limitations (Allen et al. 1998).

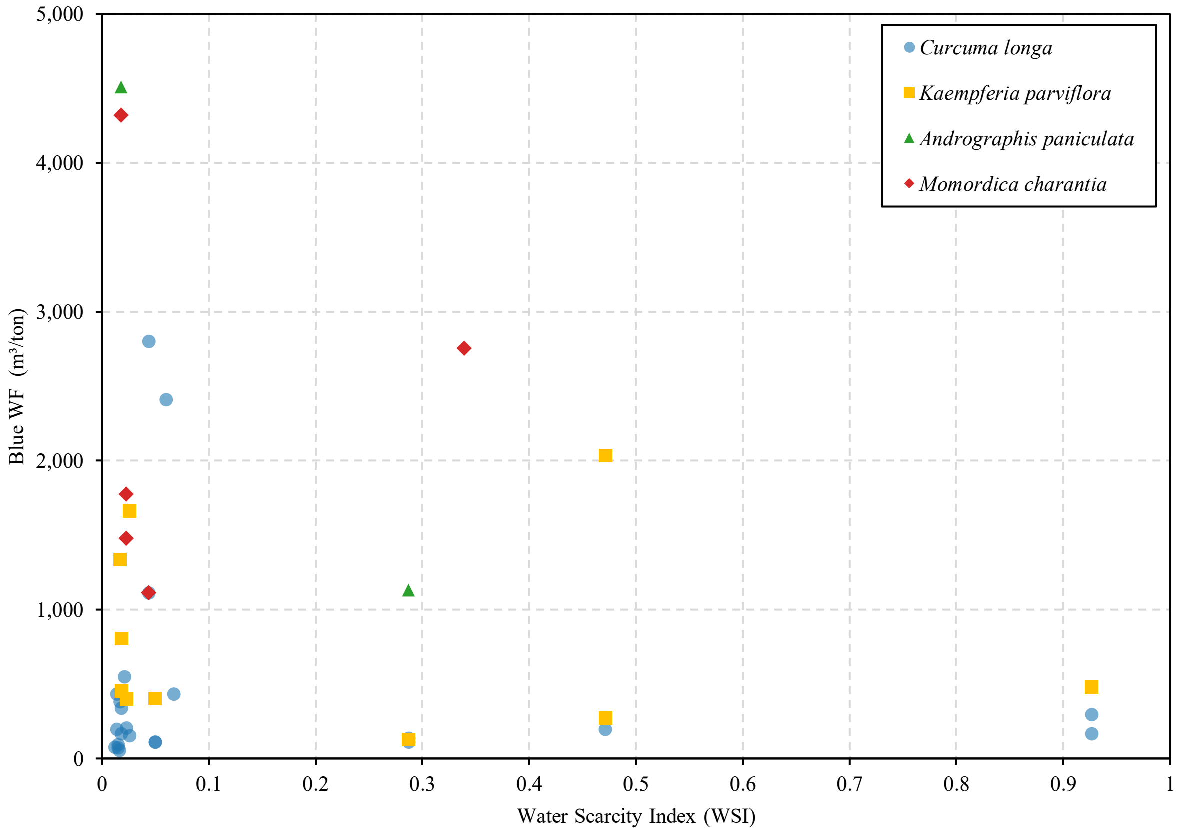


Fig. 4: Provincial blue WF versus basin-level WSI for 4 medicinal herbs.

From a management perspective, these findings support herb- and basin-specific strategies. Improving irrigation efficiency and field-level water-use management would be particularly effect in provinces where WSI is low but blue WF is high (Li et al. 2022). Conversely, in provinces where both blue WF and WSI are high, prioritizing production system adjustments or potential relocation may be more appropriate (Osborne and Sack, 2012). The interpretive emphasis thus lies on spatially targeting interventions rather than on deriving a single national correlation metric.

4.4 Limitations and Future Work

Although this assessment provides a comprehensive evaluation of the green, blue, and gray WFs of economically important Thai medicinal herbs, several limitations must be acknowledged. The first relates to data availability and spatial resolution. Climatic and agricultural datasets were aggregated at the provincial level, which may obscure local-scale variability in farming practices, irrigation performance, and microclimatic conditions. Likewise, the use of long-term climatic averages may mask inter-annual fluctuations in evapotranspiration and effective rainfall, particularly under increasingly variable monsoon conditions.

Second, the gray WF estimates rely on generalized parameter values for nitrogen leaching fractions and threshold nitrate concentrations. Although these values are consistent with WFN recommendations, regional differences in soil-water interactions and fertilizer management may lead to deviations from the assumed conditions. Future work would benefit from site-specific nitrogen leaching measurements and probabilistic modeling frameworks to better represent uncertainty and capture spatial heterogeneity.

Third, the present study focuses solely on the cultivation stage. Post-harvest processes-including drying, extraction, and primary processing-were excluded to maintain consistency with WFN methodological boundaries. However, these downstream stages may substantially increase total WF, especially when herbs undergo intensive processing for medicinal or nutraceutical applications. Incorporating these stages within a more comprehensive life-cycle framework would enhance the policy relevance of future assessments.

Finally, this study does not account for economic or social dimensions of water use, such as value added per unit of water or farmer exposure to water scarcity. Including such indicators would enable a multidimensional evaluation of water productivity, integrating biophysical, economic, and social-justice perspectives.

Future research should therefore concentrate on developing high-resolution, site-specific datasets that more accurately capture agroecological variability, while also integrating water-footprint results with other environmental indicators-such as carbon and land-use footprints-to reveal potential cross-impact trade-offs. In parallel, embedding an economic and social valuation perspective into future assessments would allow the optimization of herb production systems under Thailand’s net-zero and BCG policy initiatives. Such integrated approaches will enhance the robustness of decision-making for sustainable water allocation and climate-smart medicinal herb cultivation.

5. CONCLUSIONS

This study successfully quantified the green, blue, and gray water footprints (WF) of four economically significant Thai medicinal herbs—*Curcuma longa*, *Kaempferia parviflora*, *Andrographis paniculata*, and *Momordica charantia*—using the standardized WFN methodology. The results demonstrate that water resource appropriation varies substantially across species, with blue water being the dominant component for most herbs, reflecting a high dependency on irrigation systems within Thailand’s agricultural sector.

Among the studied species, *Curcuma longa* exhibited the most favorable water-use profile with the lowest total WF, primarily due to its high reliance on green water and suitability for rain-fed cultivation. Conversely, *Momordica charantia* and *Andrographis paniculata* showed significantly higher water intensities, particularly in regions where intensive irrigation is required to maintain yields. Spatial analysis further identified critical geographic hotspots, such as Ratchaburi and Khon Kaen, where high blue WF values coincide with basins experiencing moderate-to-high water scarcity, indicating potential risks to local water security.

Sensitivity analysis confirmed that crop yield is the most critical factor influencing the total WF across all species. This finding highlights that agronomic improvements aimed at yield enhancement remain the most effective strategy for reducing the volumetric water footprint per ton of product. Furthermore, benchmarking these results against major food and industrial crops suggests that even relatively efficient herbs can exert substantial pressure on freshwater resources if cultivation scales rapidly without proper water management.

In conclusion, the findings provide a robust evidence-based foundation for sustainable water planning in the herbal sector. To mitigate environmental impacts, policy interventions should prioritize the adoption of water-saving irrigation technologies, site-specific nutrient management, and crop zoning aligned with regional water availability. These strategies will be essential for balancing the economic expansion of Thailand's medicinal herb industry with the long-term sustainability of national water resources.

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REFERENCES

1. Ababaei, B. and Etedali, H.R., 2016. Water footprint assessment of main cereals in Iran. *Agricultural Water Management*, 179, pp. 401–411. https://doi.org/10.1016/j.agwat.2016.07.016.
2. Allen, R.G., Pereira, L.S., Raes, D. and Smith, M., 1998. Crop evapotranspiration: Guidelines for computing crop water requirements (FAO Irrigation and Drainage Paper No. 56). FAO, Rome, Italy. Available at: https://www.fao.org/3/x0490e/x0490e00.htm (Accessed: 14 October 2025).
3. Chaibandit, K., Konyai, S. and Slack, D.C., 2017. Evaluation of the water footprint of sugarcane in eastern Thailand. *Engineering Journal*, 21(5), pp. 193–201. https://doi.org/10.4186/ej.2017.21.5.193.
4. Chanakanachai, W. and Lekunwong, S., 2000. Guide for cultivation of herbal plants (1st ed., in Thai). Department of Agricultural Extension, Ministry of Agriculture and Cooperatives, Bangkok, Thailand.
5. Department of Thai Traditional and Alternative Medicine, 2023. Announcement on herbal champion products B.E. 2566 (in Thai). Ministry of Public Health, Thailand.

6. Gheewala, S.H., Silalertruksa, T., Nilsalab, P., Mungkung, R., Perret, S.R. and Chaiyawannakarn, N., 2014. Water footprint and impact of water consumption for food, feed, fuel crops production in Thailand, *Water*, 6(6), pp. 1698–1718. https://doi.org/10.3390/w6061698.
7. Hoekstra, A.Y., Chapagain, A.K., Aldaya, M.M. and Mekonnen, M.M., 2011. The water footprint assessment manual: Setting the global standard. Earthscan, London, UK.
8. Hoekstra, A.Y. and Mekonnen, M.M., 2012. The water footprint of humanity, *Proceedings of the National Academy of Sciences*, 109(9), pp. 3232–3237. https://doi.org/10.1073/pnas.1109936109.
9. Kaewjampa, N., Chaisri, N. and Boonthaiwai, C., 2016. Comparison of the water footprint of cassava and sugarcane in Northeast Thailand. International Journal of Environmental and Rural Development, 7(2): 18–23.
10. Li, Z., Wu, H. and Deng, X., 2022. Spatial pattern of water footprints for crop production in northeast China, *Sustainability*, 14(20), p. 13649. https://doi.org/10.3390/su142013649.
11. Lovarelli, D., Bacenetti, J. and Fiala, M., 2016. Water Footprint of crop productions: A review, *The Science of the Total Environment*, 548–549, pp. 236–251. https://doi.org/10.1016/j.scitotenv.2016.01.022.
12. Mekonnen, M.M. and Hoekstra, A.Y., 2011. The green, blue and grey water footprint of crops and derived crop products, *Hydrology and Earth System Sciences*, 15(5), pp. 1577–1600. https://doi.org/10.5194/hess-15-1577-2011.
13. Mekonnen, M.M. and Hoekstra, A.Y., 2014. Water footprint benchmarks for crop production: A first global assessment, *Ecological Indicators*, 46, pp. 214–223. https://doi.org/10.1016/j.ecolind.2014.06.013.
14. Mekonnen, M.M. and Hoekstra, A.Y., 2020. Sustainability of the blue water footprint of crops, *Advances in Water Resources*, 143, p. 103679. https://doi.org/10.1016/j.advwatres.2020.103679.
15. Ministry of Higher Education Science Research and Innovation (MHESRI), 2019. BCG in action: the new sustainable growth engine-model for sustainable development economics (in Thai). Ministry of Higher Education Science Research and Innovation, Thailand.
16. Mungkung, R., Gheewala, S.H., Silalertruksa, T. and Dangsiri, S., 2019. Water footprint inventory database of Thai rice farming for water policy decisions and water scarcity footprint label, *The International Journal of Life Cycle Assessment*, 24(12), pp. 2128–2139. https://doi.org/10.1007/s11367-019-01648-0.
17. Ngamsomjit, W., 2008. Study of water consumption of five medicinal herbs: Year 3 (in Thai). Royal Irrigation Department, Bangkok, Thailand.
18. Osborne, C.P. and Sack, L., 2012. Evolution of C 4 plants: a new hypothesis for an interaction of CO 2 and water relations mediated by plant hydraulics, *Philosophical Transactions of the Royal Society B Biological Sciences*, 367(1588), pp. 583–600. https://doi.org/10.1098/rstb.2011.0261.
19. Ratchawat, T., Panyatona, S., Nopchinwong, P., Chidthaisong, A. and Chiarakorn, S., 2018. Carbon and water footprint of Robusta coffee through its production chains in Thailand,' *Environment Development and Sustainability*, 22(3), pp. 2415–2429. https://doi.org/10.1007/s10668-018-0299-4.
20. Suttayakul, P., Kittikun, A., Suksaroj, C., Mungkalasiri, J., Wisansuwannakorn, R. and Mukikavong, C., 2015. Water footprints of products of oil palm plantations and palm oil mills in Thailand, *The Science of the Total Environment*, 542(Pt A), pp. 521–529. https://doi.org/10.1016/j.scitotenv.2015.10.060.