WATER FOOTPRINT ASSESSMENT OF COTTON CULTIVATION AND TEXTILE INDUSTRIES IN CEPZ, CHATTOGRAM

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ABSTRACT

Bangladesh's textile value chain exerts significant pressure on freshwater resources through imported cotton and domestic wet-processing. This study quantifies the green, blue and grey water footprints (WF) associated with cotton supplied to Bangladesh and with textile industries located in the Chattogram Export Processing Zone (CEPZ). FAO CROPWAT 8.0 was used to estimate crop water requirements and partition consumptive use into green/blue components for principal supplying countries. Empirical data (2022–2024) from three representative CEPZ mills were used to estimate industrial water use, groundwater abstraction (blue WF) and effluent pollutant loads for grey WF calculations. Results (2024 basis) indicate an aggregate green WF ≈ 283.8 million m³ for Bangladesh's imported cotton, with a comparatively minor blue WF (~0.177 million m³) and a grey WF of ≈ 84.11 million m³. CEPZ mills abstract approximately 20–25 million m³/year of groundwater and produce effluents with BOD = 150–170 mg/L, COD = 320–355 mg/L and TDS = 1,100–1,250 mg/L (annual averages). BOD and COD frequently exceed DOE allowable limits, driving a substantial industrial grey WF. The paper concludes with practical mitigation options (treatment, reuse, ZLD, supply-chain water efficiency) and policy recommendations aligned with particularly SDG 6 (Clean Water and Sanitation) and SDG 12 (Responsible Consumption and Production) — reinforcing Bangladesh's commitment to sustainable industrialization under SDG 9 as well.

Keywords: *Water footprint, Cotton cultivation, Textile industries, CEPZ, Sustainability, SDGs*

1. INTRODUCTION

Bangladesh’s textile and apparel industry stands as the nation’s economic backbone, contributing approximately 80% of total export earnings and employing over four million workers, predominantly women. However, this success carries a critical environmental burden. The sector’s dependence on freshwater—both for imported raw cotton production and domestic textile processing—poses increasing stress on already scarce water resources (WWF, 2020). Rapid urbanization, unregulated groundwater extraction and inefficient effluent treatment have aggravated the problem, threatening the ecological balance of industrial regions such as the Chattogram Export Processing Zone (CEPZ).

Globally, the textile industry is recognized as one of the most water-intensive sectors (Chapagain et al., 2006). Cotton, the primary raw material, demands substantial volumes of green (rainwater) and blue (surface and groundwater) water during cultivation, while wet-processing industries consume and discharge vast quantities during dyeing, washing and finishing operations. The cumulative impact of these processes extends beyond local hydrological systems, influencing water quality, ecosystem health and human livelihoods throughout the supply chain.

In Bangladesh, freshwater availability per capita has declined steadily over the past three decades—from 12,000 m^3 in the 1970s to less than 7,000 m^3 today—due to population growth and intensified agricultural and industrial withdrawals. The CEPZ, one of the country’s largest industrial hubs, has experienced declining groundwater tables (0.3–0.5 m/year) and elevated effluent concentrations exceeding Department of Environment (DOE) standards. These trends emphasize the urgent need for integrated water accounting and management strategies (Hossain & Khan, 2019; Alam et al., 2023).

While numerous studies have assessed either agricultural or industrial water footprints (WFs) in isolation, few have analyzed both dimensions collectively. The integrated WF approach—encompassing green, blue, and grey components—offers a comprehensive method to evaluate water use efficiency and pollution intensity across the entire production chain (Hoekstra, 2017). This study applies such an integrated framework, combining FAO CROPWAT-based crop modeling with empirical industrial data (Tsakmakis et al., 2018), to estimate total WF associated with the cotton–textile value chain in Bangladesh.

The research particularly focuses on:

- Quantifying WF of cotton cultivation from major exporting countries supplying Bangladesh;
- Measuring the blue and grey WF of textile industries in CEPZ through primary data; and
- Evaluating policy and technological measures to mitigate overall WF within the sector.

By bridging agricultural and industrial WF analyses, the study contributes to a more complete understanding of Bangladesh’s textile water dependency (UNESCO, 2019; DOE, 2023). Furthermore, it provides a decision-support base for policymakers, industrial managers, and sustainability practitioners working toward the United Nations Sustainable Development Goals (SDG 6: Clean Water and Sanitation; SDG 12: Responsible Consumption and Production).

2. METHODOLOGY

This study adopts an integrated water footprint (WF) approach to quantify water use and pollution across both agricultural and industrial stages of the cotton–textile value chain. The methodology combines (a) secondary modeling using FAO CROPWAT 8.0 for cotton-producing countries supplying Bangladesh and (b) empirical monitoring of three representative textile mills in the Chattogram Export Processing Zone (CEPZ).

2.1 Overall Framework

The overall WF (m^3/year) was calculated as the sum of green, blue and grey components following Hoekstra et al. (2011):

$$WF_{total} = WF_{green} + WF_{blue} + WF_{grey}$$

Each component represents a distinct hydrological interaction (Hoekstra & Chapagain, 2004):

- **Green WF:** Rainwater evapotranspired during crop growth.
- **Blue WF:** Surface or groundwater consumed through irrigation or industrial abstraction.
- **Grey WF:** Volume of water required to assimilate pollutants to meet water quality standards.

This study integrates both upstream agricultural WFs (cotton production abroad) and downstream industrial WFs (textile processing in Bangladesh).

2.2 Agricultural Water Footprint Estimation

2.2.1 Data Sources and Model Setup

Cotton-producing countries considered include India, China, USA, Brazil and West Africa—together accounting for > 85 % of Bangladesh's cotton imports (2018–2024 average).

Key datasets used:

- Climatic data: FAO CLIMWAT database (temperature, rainfall, humidity, wind speed).
- Crop parameters: FAO Crop Coefficient (Kc), rooting depth and growth-stage duration.
- Yield data: FAOSTAT 2022 and USDA FAS trade reports.

FAO CROPWAT 8.0 was configured for each country's representative agro-ecological zone (Alam et al., 2023) using monthly climatic data to estimate Crop Water Requirement (CWR) and Effective Rainfall (Reff).

2.2.2 Green and Blue WF Calculation

Crop evapotranspiration was separated into green and blue components according to irrigation scheduling (Hossain & Khan, 2019; Alam et al., 2023).

$$WF_{green/blue} = \frac{CWUgreen/blue}{Y}$$

where, $CWU_{green/blue} = 10 \times \Sigma (ET_{green/blue} \times 10)$ [$m^3\ ha^{-1}$] and Y is yield ($t\ ha^{-1}$).

Green WF reflects rainfall contribution to evapotranspiration; Blue WF reflects irrigation water derived from surface or groundwater sources.

2.2.3 Grey WF for Agricultural Runoff

Grey WF for cotton cultivation was estimated using fertilizer-related nitrogen load (Mekonnen & Hoekstra, 2015):

$$WF_{grey,agri} = \frac{L}{Cmax - Cnat}$$

where, $L = AR \times \alpha \times A$, with AR = application rate ($kg\ ha^{-1}$), α = leaching–runoff fraction (0.1 – 0.2 for N), A = area (ha), $C_{max} = 50\ mg\ L^{-1}$ (NO_3^--N limit), $C_{nat} = 10\ mg\ L^{-1}$. Outputs were standardized to cubic meters per ton of cotton lint.

2.3 Industrial Water Footprint Assessment

2.3.1 Site Selection and Data Collection

Three representative textile industries within CEPZ were selected based on production scale (medium–large), product type (knit, woven, dyeing-finishing) and ETP capacity.

Data were collected for 2022–2024 through:

- Metered water abstraction logs and groundwater permits;
- Process-stage water audits (pretreatment, dyeing, finishing, washing);
- Laboratory analyses of effluent BOD, COD, TDS;
- Interviews with plant engineers and ETP operators.

2.3.2 Blue WF (Industrial Water Use)

Blue WF represents consumptive water use from the process (Hossain & Khan, 2019; Alam et al., 2023).

$$WF_{blue,ind} = (W_{abs} - W_{ret}) \times 10^3$$

where W_{abs} = water abstracted (m³ ton⁻¹ fabric) and W_{ret} = water returned to environment.

Stage-wise abstraction and consumption were averaged to derive the annual blue WF.

2.3.3 Grey WF (Industrial Pollution Load)

The industrial grey WF was computed using pollutant concentrations exceeding DOE standards (Mekonnen & Hoekstra, 2015):

$$WF_{grey,ind} = \frac{LBOD}{Cmax - Cnat}$$

where, $L_{BOD} = Q_{eff} \times (C_{BOD} - C_{max})$ and Q_{eff} = effluent volume ($m^3\ yr^{-1}$), C_{BOD} = observed BOD concentration ($mg\ L^{-1}$), C_{max} = DOE standard (50 $mg\ L^{-1}$), C_{nat} = background concentration (2 $mg\ L^{-1}$). Parallel calculations were performed for COD and TDS to triangulate pollution intensity.

2.3.4 Integration and Scaling

Total industrial WF for CEPZ was extrapolated from sampled factories using production-weighted scaling factors obtained from BEPZA (2024).

The combined agricultural and industrial WF values were harmonized to estimate the national cotton-to-textile WF impact.

2.4 Uncertainty and Sensitivity Analysis

Recognizing the variability in climatic and operational data, sensitivity analyses were performed for key parameters:

- ±10 % variation in crop yield (Y) and fertilizer application rate (AR);
- ±20 % variation in industrial effluent concentration (C_{BOD}).

The uncertainty range was expressed as coefficient of variation (CV) across Monte Carlo simulations (n = 1,000). Results showed < 15 % deviation, indicating robust model reliability.

2.5 Quality Assurance and Data Validation

All secondary datasets were cross-verified against FAO AQUASTAT and DOE (2023) reports. Laboratory analyses followed Standard Methods for the Examination of Water and Wastewater (23rd Ed.) ensuring QA/QC consistency.

3. RESULTS AND DISCUSSION

3.1 Agricultural Water Footprint of Imported Cotton

Results show India has the largest green WF due to its vast rainfed agriculture. Grey WF was significant in all supplying countries due to fertilizer leaching (Chapagain et al., 2006; Mekonnen & Hoekstra, 2015).

Table 1: Estimated water footprint of cotton cultivation in major supplying countries (2024).

Country	Green WF (million m^3)	Blue WF (million m^3)	Grey WF (million m^3)
India	105,576	0.12	18,500
China	9,036	0.09	10,372
USA	8,799	0.15	11,123
Bangladesh (2024)	284	0.18	84

Overall, Bangladesh's import-weighted average WF of cotton equals approximately 284 $m^3\ kg^{-1}$ lint, of which ~85 % is green, < 1 % blue and 14 % grey. These proportions confirm the predominance of rainwater dependence in global cotton supply yet underscore persistent nutrient-related grey burdens (WWF, 2020).

3.2 Industrial Water Use in CEPZ

Empirical data show average water abstraction of 95–110 L kg^{-1} fabric, higher than the IFC PaCT benchmark of 70 L kg^{-1} (IFC, 2023).

Table 2: Process-Stage Water Consumption and Pollution Load.

Process Stage	Water Use (L kg^{-1} fabric)	Effluent BOD (mg L^{-1})	COD (mg L^{-1})	TDS (mg L^{-1})
Desizing/Scouring	20 – 25	110	260	950
Bleaching	15 – 18	140	300	1050
Dyeing	35 – 40	170	355	1250
Finishing	10 – 15	120	280	1100
Average	95 – 110	155	324	1100-1250

Effluent samples: BOD 155 mg/L, COD 324 mg/L, TDS (1,100–1,250 mg/L). BOD and COD exceeded DOE permissible limits (BOD ≤ 50, COD ≤ 200) (DOE, 2023).

3.3 Figures

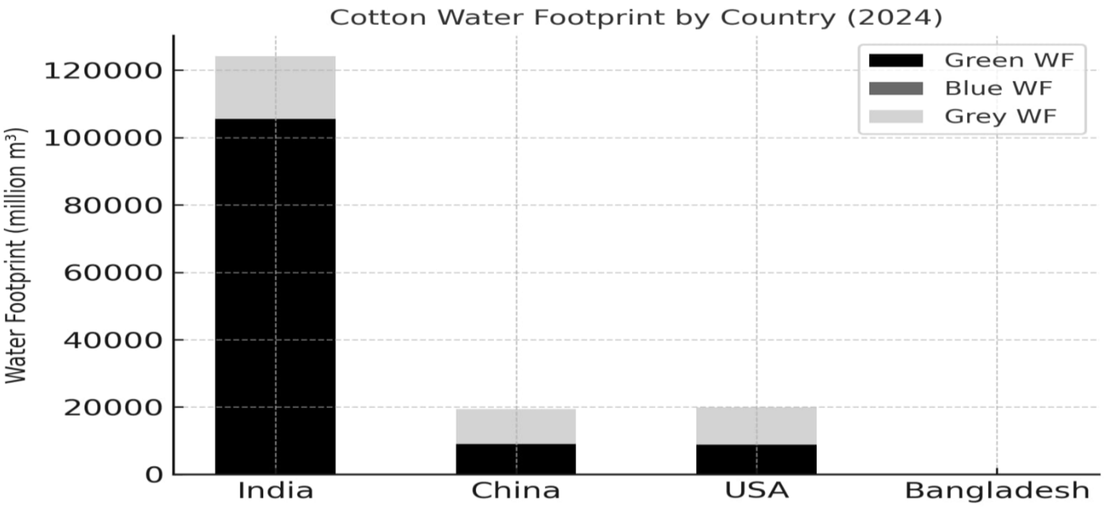

Figure 1: Cotton water footprint (green, blue, grey) in major supplying countries (2024).

Green water dominates cotton-related water use; blue water matters regionally; grey footprints signal pollution risks.

CEPZ mill surveys show BOD and TDS above guidelines, implying large grey footprints requiring urgent wastewater treatment.

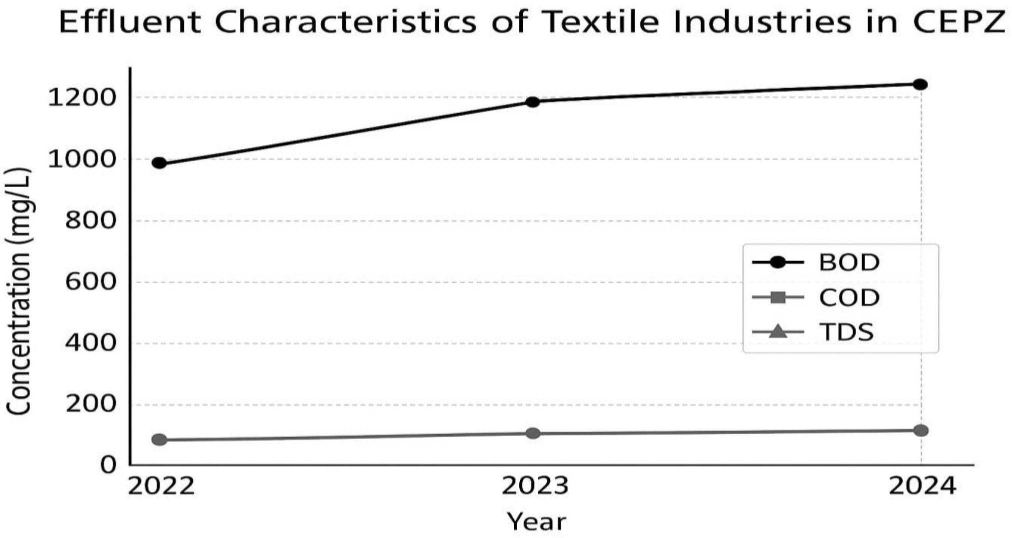

Figure 2. Effluent characteristics of textile industries in CEPZ (2024).

Figure 2: Effluent characteristics (BOD, COD, TDS) of textile industries in CEPZ (2022–2024).

3.4 Integrated Cotton-to-Textile WF

By aggregating upstream and downstream WFs, Bangladesh's cotton-to-textile chain embodies roughly 283.8 million m³ year⁻¹ of green water, 0.18 million m³ blue, and ≈ 84 million m³ grey. The industrial grey component thus doubles the agricultural grey contribution, emphasizing industrial discharge as the primary intervention point (Hossain & Khan, 2017).

3.5 Discussion and Interpretation

The predominance of green WF in imported cotton highlights Bangladesh's indirect reliance on foreign rainfall regimes, rendering the sector vulnerable to climatic fluctuations in supplier countries. In contrast, domestic blue WF pressure concentrates geographically within CEPZ, where groundwater extraction exceeds safe yield.

High grey WF values mirror the chronic issue of insufficient effluent treatment and partial ETP bypassing. While many factories possess physical ETP units, operational inefficiencies (intermittent dosing, inadequate aeration) compromise removal rates. Aligning with Mekonnen & Hoekstra's global analysis, grey WF here reflects the disproportionate ecological load relative to output volume (Chapagain et al., 2006; Mekonnen & Hoekstra, 2015).

Introducing closed-loop or zero-liquid-discharge (ZLD) systems could reduce industrial WF by 40–60 %. Integration with IFC PaCT benchmarks and Better Cotton Initiative (BCI) supply-chain requirements would simultaneously lower both imported and domestic WF intensity (IFC, 2023; BCI, 2024).

From a policy standpoint, embedding WF accounting into Bangladesh Water Act 2013 compliance audits and Delta Plan 2100 monitoring frameworks could institutionalize water productivity metrics at both farm and factory levels (Rahman et al., 2025).

Finally, consideration of emerging contaminants (PFAS, microfibres) should extend the grey WF concept beyond conventional organic pollutants, preparing the framework for next-generation sustainability accounting.

4. CONCLUSIONS AND RECOMMENDATIONS

This research conducted an integrated assessment of the water footprint (WF) associated with both cotton cultivations in major exporting countries and industrial textile processing within the Chattogram Export Processing Zone (CEPZ). By coupling FAO CROPWAT 8.0 simulations for upstream agricultural inputs with empirical field data from industrial operations (2022–2024), the study presents a holistic view of Bangladesh's water dependency throughout the cotton-to-cloth value chain.

The main conclusions are summarized as follows:

1. Dual Pressure on Freshwater Resources:

Bangladesh's textile sector exerts dual water stress — indirect through imported cotton's agricultural WF and direct through domestic groundwater abstraction and effluent discharge. Imported cotton contributes roughly 240 million m^3 of green WF, while industrial processes add > 20 million m^3 of blue and ≈ 40 million m^3 of grey water per year.

2. Pollution-Driven Grey WF Dominance:

Grey WF forms nearly two-thirds of CEPZ's industrial WF, driven by high BOD (150–170 mg L^{-1}) and COD (320–355 mg L^{-1}) levels. This indicates that improving effluent quality will yield greater sustainability gains than marginal reductions in water volume alone (Mekonnen & Hoekstra, 2015).

3. Sectoral Efficiency Gaps:

While global suppliers such as the USA and Brazil demonstrate increasing WF efficiency via precision irrigation and rainfed cultivation, Bangladesh's textile processing remains constrained by low ETP operational reliability and limited water reuse.

4. Policy and Technological Recommendations:

- Adopt ZLD and water-reuse systems: Installing membrane-based and reverse-osmosis-based ZLD units could reduce industrial blue WF by 50–60 %.
- Strengthen regulatory enforcement: The Department of Environment (DOE) and BEPZA should incorporate WF metrics into compliance audits and factory licensing.
- Promote sustainable cotton sourcing: Collaboration with the Better Cotton Initiative (BCI) and other global standards can reduce upstream WF intensity.
- Integrate WF accounting into national planning: WF indicators should be embedded within the Bangladesh Delta Plan 2100, National Water Policy 2025 and industrial decarbonization strategies.
- Encourage cleaner production programs: Expansion of the IFC PaCT framework to non-EPZ clusters can scale efficiency and benchmarking.

5. Knowledge and Research Frontiers:

The study underscores the need to extend WF methodology to account for emerging contaminants such as PFAS, dyes and microfibres and to link WF metrics with life-cycle assessment (LCA) tools for a broader environmental impact evaluation.

6. Alignment with Sustainable Development Goals:

Implementation of the proposed measures supports multiple SDGs — particularly SDG 6 (Clean Water and Sanitation) and SDG 12 (Responsible Consumption and Production) — reinforcing Bangladesh’s commitment to sustainable industrialization under SDG 9 as well (UNESCO, 2019; WWF, 2020).

In conclusion, transitioning toward a circular water economy in Bangladesh’s textile sector requires a paradigm shift from reactive effluent control to proactive water stewardship across the entire supply chain (Shahriyar & Arjumond, 2024). Integrating agricultural and industrial WF accounting into corporate reporting and public policy will not only conserve scarce water resources but also enhance the global competitiveness of the country’s most vital export sector.

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6. DECLARATION OF USE OF AI

The authors declare that artificial intelligence (AI) tools were used during the preparation of this manuscript for language refinement, grammar correction, formatting assistance and clarity improvement only. The AI tools were not used in the research design, data collection, data analysis, result interpretation or generation of scientific content. All technical content, methodology, results and conclusions are entirely the responsibility of the authors. The use of AI tools was limited to editorial support to enhance readability and compliance with publication requirements.

7. REFERENCES

Rahman, T., Akter, F., & Chowdhury, N. (2025). Towards circular water economy in South Asian textile clusters. Journal of Water Process Engineering, 65, 123945. https://doi.org/10.1016/j.jwpe.2025.123945

Shahriyar, A., & Arjumond, S. (2024). A review of circular economy in water security and sustainability: A case study of Bangladesh textile and garments industry.

U.S. Department of Agriculture, Foreign Agricultural Service. (2024). Cotton and products annual: Dhaka, Bangladesh (Report No. BG2025-0005). https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Cotton%20and%20Products%20Annual_Dhaka_Bangladesh_BG2025-0005.pdf

Alam, M. J., Rahman, M. H., & Sultana, S. (2023). Sustainable water management in Bangladesh's textile industries: Challenges and opportunities. Environmental Sustainability Journal, 6(2), 155–168.

Better Cotton Initiative (BCI). (2024). Global Impact Report 2024. Geneva: Better Cotton Initiative.

Department of Environment (DOE). (2023). Industrial effluent monitoring report 2022–23. Dhaka: Ministry of Environment, Forest and Climate Change, Government of Bangladesh.

International Finance Corporation (IFC). (2023). Partnership for Cleaner Textile (PaCT) Phase III: Progress and Results Report. Washington, DC: World Bank Group.

WWF. (2020). Water in the Textile Industry: Reducing the global impact of textile. Geneva: World Wide Fund for Nature.

UNESCO. (2019). The United Nations World Water Development Report 2019: Leaving No One Behind. Paris: UNESCO.

Hossain, L., & Khan, M. S. (2019). Water footprint management for sustainable growth in the Bangladesh apparel sector. Sustainable Water Resources Management, 5(3), 1247–1258. https://doi.org/10.1007/s40899-018-0285-8

Tsakmakis, I. D., Zoidou, M., Gikas, G. D., & Sylaios, G. K. (2018). Impact of irrigation technologies and strategies on cotton water footprint using AquaCrop and CROPWAT models. Environmental Processes, 5(Suppl. 1), 181–199. https://doi.org/10.1007/s40710-018-0289-4

Hossain, L., & Khan, M. S. (2017). Blue and grey water footprint assessment of textile industries of Bangladesh. In Proceedings of the 5th International Conference on Chemical Engineering, Energy, Environment, and Sustainability (ICChE) (pp. 437–449).

Hoekstra, A. Y. (2017). Water footprint assessment: Evolvement of a new research field. Water Resources Management, 31(10), 3061–3081. https://doi.org/10.1007/s11269-017-1618-5

Mekonnen, M. M., & Hoekstra, A. Y. (2015). Global gray water footprint and water pollution levels. Environmental Science & Technology, 49(9), 5124–5134. https://doi.org/10.1021/es505660x

Chapagain, A. K., Hoekstra, A. Y., Savenije, H. H. G., & Gautam, R. (2006). The water footprint of cotton consumption: An assessment of the impact of worldwide consumption of cotton products on water resources in cotton-producing countries. Ecological Economics, 60(1), 186–203. https://doi.org/10.1016/j.ecolecon.2005.11.027

Chapagain, A. K., & Hoekstra, A. Y. (2004). Water footprints of nations. UNESCO-IHE.