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Export Concentration and Industrial Carbon Emissions in Bangladesh: Implications for Textile Sector Decarbonisation

Tahsin Shabab Rajee[1*], Sinthia Tasnim[2], Hafsa Binte Karim Benoy[3] and Md. Abid Hasan[2]

[1]Department of Finance, Independent University, Bangladesh, Dhaka - 1229, Bangladesh

[2]Department of Environmental Science and Engineering, Bangladesh University of Textiles, Dhaka - 1208, Bangladesh

[3]Department of Textile Engineering Management, Bangladesh University of Textiles, Dhaka - 1208, Bangladesh

Abstract

Export-led industrialisation can concentrate environmental risk in a single carbon-intensive subsector, yet studies that examine trade and emissions in aggregate often miss this dynamic entirely. This paper investigates whether the expansion of Bangladesh's textile exports, rather than manufacturing activity more broadly, has been the principal driver of the country's rising industrial carbon emissions, using annual data spanning three decades and a dynamic time-series framework suited to small samples and structural change. The results show that textile export growth exerts a strong and lasting influence on industrial emissions, while broader manufacturing activity does not, once the textile sector's role is accounted for. The relationship is unidirectional, running from exports to emissions, and remains consistent across alternative estimation approaches applied as robustness checks. These findings indicate that decarbonisation efforts should target the textile value chain directly, particularly its most energy-intensive processes, rather than relying on economy-wide manufacturing policy, offering transferable lessons for other textile-dependent exporting economies facing similar structural pressures.

Major Findings: Textile export expansion, not aggregate manufacturing growth, is the dominant force behind Bangladesh's industrial emissions trajectory, with causality flowing from exports to emissions rather than the reverse, underscoring the need for sector-specific decarbonisation policy.

Keywords: ARDL Bounds Testing, Bangladesh, Decarbonisation, Export Concentration, Industrial Carbon Emissions, Textile Exports

1. Introduction

Bangladesh's Ready-Made Garment (RMG) sector has grown rapidly over the past three decades, and so has its contribution to the national economy: the industry now contributes more than 80 per cent of the country's total export earnings, having transformed Bangladesh into one of the world's largest apparel exporters (Islam, 2022). This growth trajectory has been mirrored by a parallel, steep rise in national carbon output, with CO_2 emissions increasing more than six-fold, from 14.08 million tons in 1990 to 92.8 million tons by 2020 (Jabbar *et al.*, 2022). The near-simultaneous rise of an export-oriented textile economy and national emissions invites a foundational question that empirical trade-environment studies have not fully resolved: does trade-driven expansion of a single carbon-intensive sector alter, or merely mirror, the broader economy-emissions relationship that development theory predicts.

*Email: [1]shababrajee02@gmail.com

Two theoretical traditions bear on this question. The Environmental Kuznets Curve (EKC) hypothesis holds that emissions rise with economic growth before eventually declining once income and technological capacity cross a critical threshold (Grossman & Krueger, 1994), implying that Bangladesh's rising emissions may reflect an early and transitional growth phase rather than a permanent trajectory. The pollution haven and composition-effect literatures instead emphasise that the sectoral structure of trade, rather than income growth alone, determines environmental outcomes: Zhang and Wang (2021) demonstrate that final-product trade patterns concentrate pollution within specific economies, while Wu *et al.* (2025) and Shahzad *et al.* (2020) find that specialised, undiversified industrial structures generate higher emissions relative to diversified ones. These two traditions agree that trade shapes emissions but disagree on whether the operative mechanism is growth-driven convergence toward cleaner production or structural concentration in carbon-intensive sectors, a tension that is especially consequential for economies whose export base is concentrated in a single high-emission industry.

This theoretical tension is difficult to resolve using aggregate cross-sectional methods. Shahbaz *et al.* (2016) show that trade-emissions dynamics require long-run time-series approaches capable of capturing equilibrium adjustment rather than static, cross-sectional comparisons, while Huang *et al.* (2026) demonstrate that aggregating heterogeneous manufacturing subsectors obscures the marginal contribution of individual export sectors to industrial emissions. For Bangladesh specifically, Faruq *et al.* (2024) confirm EKC evidence within the aggregate CO_2-growth-energy-finance nexus, yet this analysis does not isolate the textile sector's distinct role within that relationship. Given the RMG sector's outsized economic weight, this omission leaves the central sectoral channel empirically untested. This paper addresses that gap by examining whether textile export expansion drives industrial carbon emissions in Bangladesh, testing whether this sector-specific channel is better explained by structural concentration in a carbon-intensive export industry than by the growth-driven convergence the EKC predicts, using an Auto-regressive Distributed Lag (ARDL) bounds testing framework augmented with structural break controls, applied to annual data spanning 1994 to 2024.

2. Literature Review

The theoretical relationship between export-led industrialisation and environmental degradation involves competing scale, composition, and efficiency mechanisms. Yi and Qamruzzaman (2024) again confirm the EKC hypothesis in Bangladesh, finding that economic growth initially increases carbon emissions before environmental improvements emerge at higher development stages. Ghazal *et al.* (2024) analyse 67 developing countries, demonstrating that while expanding economic activity generates scale effects that raise emissions, efficiency gains from transitioning toward high-tech industries and cleaner energy ultimately dominate. Liu *et al.* (2026) show that environmental regulations trigger divergent abatement strategies wherein large firms adopt technological governance approaches while small firms reduce output, catalysing industrial concentration that restructures emissions trajectories. The environmental consequences of export growth therefore depend on technological capacity, regulatory design, and industrial composition rather than trade expansion alone.

Cross-country evidence reveals heterogeneity in the export-emissions relationship varying by economic complexity, global value chain (GVC) position, and regulatory context. Qayyum *et al.* (2021) demonstrate asymmetric impacts between high-income and low- and middle-income countries, finding that economic complexity reduces the marginal effects of export scale and structure on embodied carbon emissions in foreign markets, though not in domestic production. Wu and Chen (2025) report that longer production chains positively correlate with both production-side and consumption-side emissions, with developing countries experiencing more pronounced impacts, while Zhou *et al.* (2022) find that GVC embedment reduces carbon emissions embodied in exports through energy conservation, structural change, and transfer effects, though these reductions concentrate in low-tech industries and under complex forward embedment. Recent studies identify nonlinear dynamics. Bakri *et al.* (2025) identify a threshold effect across 22 Asian

countries wherein trade openness initially raises emissions before inducing reductions beyond a critical level, and Du *et al.* (2023) show that environmental regulations promote the intensive margin of clean product exports through cost effects, with market-based instruments proving more effective than command-and-control approaches.

Against this backdrop, Bangladesh's RMG sector, the country's export powerhouse, is highly carbon-intensive and raises serious environmental concerns. Globally, the textile industry accounts for 6 to 8 per cent of emissions, with carbon intensity concentrated in yarn and fabric production, particularly wet processing stages where dyeing and finishing operations drive emissions through reliance on coal and natural gas (Sharpe *et al.*, 2022). In Bangladesh, Biswas *et al.* (2024) document that RMG industries contribute 67.8 per cent and 32.2 per cent, respectively, to industrial emissions in a major production zone, with scope 1 emissions from onsite fuel combustion dominating at 85 per cent. Post-Rana Plaza reforms show uneven outcomes. Hossain and Mahmud (2025) find that green factory certifications remain concentrated among elite exporters, with persistent non-compliance among SMEs and subcontractors, while M. Hossain *et al.* (2025) show that recent sectoral reforms, such as Accord and Alliance interventions, have prioritised workplace safety over environmental protection. Raza and Hasan (2022) report that technological progress in the manufacturing sector exhibits a positive association with CO_2 emissions over the 1980 to 2018 period, though their forecasts suggest emissions growth may continue with moderating environmental effects through 2040.

Investigating such emissions-trade dynamics requires econometric approaches capable of capturing this time-varying relationship. While earlier studies relied on static techniques like Ordinary Least Squares (Jamel & Maktouf, 2017), recent research increasingly adopts dynamic models such as ARDL (Naveed *et al.*, 2022). Kadioglu *et al.* (2025) apply this approach to Turkey's green economy transition, reporting a rapid adjustment toward long-run equilibrium. Such dynamic models remain vulnerable to reverse causality between trade and emissions, but Wolde-Rufael (2009) shows, based on Monte Carlo evidence, that ARDL effectively corrects for the endogeneity of explanatory variables. This robustness, along with its suitability for small samples (Guefano, 2025), explains why studies with as few as 30 to 35 observations increasingly rely on this econometric approach (Kadioglu *et al.*, 2025; Dirir & Aden, 2025).

Time-series studies of the textile-export and emissions nexus remain scarce and methodologically uneven, as most existing work examines aggregate industrial activity rather than isolating the textile sector specifically (Rahman & Kashem, 2017). This paper addresses this gap by employing an ARDL model to identify long-run relationships between textile exports and CO_2 emissions from industrial combustion, and re-examines the Bangladesh case using a harmonised calendar-year dataset. A closely related paper by Khuky *et al.* (2022) studies textile and clothing exports' effect on environmental quality in Bangladesh using data from 1983 to 2019 and ARDL bounds-testing, finding that export expansion is associated with higher emissions. However, Bangladesh Garment Manufacturers and Exporters Association's (BGMEA) database distinguishes pre-1994 apparel figures on a fiscal-year basis from 1994 onward calendar-year figures, so combining the pre-1994 series with calendar-year emissions creates temporal-alignment problems in dynamic models. By restricting textile exports to the calendar-year series (1994 to 2024) and aligning all variables on the same time scale, this study avoids the fiscal-year and calendar-year mismatch and estimates the export and emissions relationship on a cleaner, internally consistent basis.

3. Methods

3.1 Data and Variables

This study examines the long-run relationship between industrial carbon emissions, textile exports, and manufacturing value-added in Bangladesh using annual time series data spanning 1994-2024. The dependent variable, CO2E, represents carbon dioxide emissions from industrial combustion (measured in Mt CO_2e), while the explanatory variables include

TEXP (textile exports in USD) from the Bangladesh Garment Manufacturers and Exporters Association and MNVA (manufacturing value-added as a percentage of GDP) from World Bank Open Data. All variables were transformed into natural logarithms to address scale effects and facilitate elasticity interpretation. Table 1 presents the variable summary.

3.2 Estimation Framework

The empirical strategy proceeds in two stages. First, we conduct stationarity analysis using the Augmented Dickey-Fuller (Dickey & Fuller, 1979) and Kwiatkowski-Phillips-Schmidt-Shin (Kwiatkowski *et al.*, 1992) tests implemented in Python's statsmodels package. The ADF test employs the Bayesian Information Criterion for automatic lag selection, while KPSS uses automatic lag determination based on sample size. Both tests are performed with constant-only and constant-plus-trend specifications to ensure robust inference. Given that the country experienced several abrupt economic changes during the study period (Raihan & Khan, 2022), we account for potential structural breaks that could bias conventional unit root tests by applying the Zivot-Andrews (1992) test, which endogenously identifies a single break point under the alternative hypothesis of trend stationarity. Based on the structural break identified in the MNVA series, we incorporate a step dummy variable (D2015) into subsequent modelling.

Given that preliminary tests confirm all variables are integrated of order one, we employ the ARDL bounds testing approach developed by Pesaran *et al.* (2001) to examine cointegration. This method offers several advantages for our context: it accommodates mixed orders of integration, performs well in small samples, and allows simultaneous estimation of short-run and long-run parameters. The analysis is conducted in EViews 13 using annual observations from 1996 to 2024 (n=29), with the estimation window beginning in 1996, as the two earliest observations (1994–1995) are consumed by the maximum lag order of two applied to the dependent variable. The ARDL model specification includes an unrestricted constant and no trend (Case 3), with maximum lags fixed at 2 for both the dependent and independent variables, a conservative bound appropriate for the small sample size (n=29) that also guards against over-parameterisation. The optimal lag structure ARDL(1,2,0) was selected via the Schwarz Information Criterion, which imposes a heavier penalty on additional parameters than the Akaike Information Criterion and is therefore preferred in small samples, after evaluating 18 candidate models. The general ARDL specification takes the form:

$$\Delta CO2E_t = \alpha + \sum_{i=1}^{p} \beta_i \Delta CO2E_{t-i} + \sum_{j=0}^{q_1} \gamma_j \Delta TEXP_{t-j} + \sum_{k=0}^{q_2} \delta_k \Delta MNVA_{t-k} + \theta_1 CO2E_{t-1} + \theta_2 TEXP_{t-1} + \theta_3 MNVA_{t-1} + \phi D2015 + \varepsilon_t$$

where, Δ denotes the first difference operator, p represents lags of the dependent variable, and denote lags of the explanatory variables, and is the white noise error term. Heteroskedasticity and Autocorrelation Consistent (HAC) standard errors are computed using the Bartlett kernel with a Newey-West fixed bandwidth of 4, applied as a precautionary measure to guard against potential misspecification in the residual covariance structure.

The bounds test evaluates the null hypothesis of no cointegration against the alternative of a long-run relationship, using critical values tabulated by Pesaran *et al.* (2001). As cointegration is confirmed, we estimate the long-run coefficients and derive the Error Correction Model (ECM) to quantify short-run dynamics and the speed of adjustment toward equilibrium. The ECM representation is given by:

$$\Delta CO2E_t = \alpha + \sum_{i=1}^{p-1} \beta_i \Delta CO2E_{t-i} + \sum_{j=0}^{q_1-1} \gamma_j \Delta TEXP_{t-j} + \sum_{k=0}^{q_2-1} \delta_k \Delta MNVA_{t-k} + \lambda ECT_{t-1} + \phi D2015 + \varepsilon_t$$

Table 1. Summary of variables and data sources

Variable	Definition	Source	Unit	Scale
CO2E	CO_2 and equivalent emissions from industrial combustion	World Bank	Mt CO_2e	Log
TEXP	Textile exports	BGMEA	USD	Log
MNVA	Manufacturing value added	World Bank	% of GDP	Log

where is the error correction term representing deviations from long-run equilibrium, and λ captures the speed of adjustment. Model adequacy is assessed through diagnostic tests: the Breusch-Pagan-Godfrey test for heteroskedasticity, Breusch-Godfrey LM test for serial correlation, Jarque-Bera test for normality of residuals, and Ramsey RESET test for functional form misspecification.

To assess the robustness of the long-run coefficient estimates, we supplement the ARDL framework with Dynamic Ordinary Least Squares (DOLS) and Fully Modified Ordinary Least Squares (FMOLS) as alternative cointegration estimators. DOLS addresses endogeneity and serial correlation by augmenting the cointegrating regression with leads and lags of the first-differenced regressors (Stock & Watson, 1993), implemented here with one lead and one lag. FMOLS applies a nonparametric correction to the OLS estimator to account for endogeneity and serial correlation in the cointegrated system (Phillips & Hansen, 1990). Both specifications employ the Bartlett kernel with a Newey-West fixed bandwidth of 4 for long-run covariance estimation and include the same deterministic components (constant and D2015 dummy) as the ARDL model. Pairwise Granger causality tests are conducted at two lags, consistent with the maximum lag order of the ARDL specification; following Dhar (2023), this procedure yields valid directional inference for I(1) variables confirmed to be cointegrated, as established by the bounds test in Table 5.

4. Results and Discussions

4.1 Empirical Results

The ADF and KPSS tests are applied jointly given their complementary null hypotheses: the ADF tests the null of a unit root, while the KPSS tests the null of stationarity, such that agreement across both strengthens inference. At levels, TEXP and MNVA fail to reject the ADF null under both the constant-only and constant-plus-trend specifications, while their KPSS statistics reject stationarity at the 1% level under the constant specification, with KPSS rejections extending to the trend specification at 5%, confirming non-stationarity in levels. For CO2E, the ADF statistic under the trend specification attains significance at 5% (−3.676), which could suggest trend stationarity; however, the KPSS statistic under the constant-only specification strongly rejects stationarity (0.874, $p<0.01$), and the ADF statistic without trend remains insignificant (−1.389). The joint weight of evidence under the constant specification, where both tests agree on non-stationarity, favours the I(1) classification for CO2E. Upon first differencing, all three variables reject the ADF null at the 1% level (−8.152, −6.465, and −5.447, respectively), confirming integration of order one. The uniform I(1) classification across all variables satisfies the prerequisite for ARDL bounds testing. The test results are presented in Table 2.

The Zivot-Andrews test is applied to guard against the possibility that conventional unit root tests confound

Table 2. Unit root test results (ADF and KPSS)

Variable	ADF (Level, c)	ADF (Level, ct)	ADF (1st Diff, c)	KPSS (Level, c)	KPSS (Level, ct)	Order
CO2E	-1.389	-3.676**	-8.152***	0.874***	0.081	I(1)
TEXP	-2.018	-0.474	-6.465***	0.869***	0.165**	I(1)
MNVA	0.046	-2.872	-5.447***	0.750***	0.189**	I(1)

Notes: ADF tests the null of a unit root, while KPSS tests the null of stationarity. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Table 3. Zivot–Andrews structural break test results

Variable	c (Stat)	Break	t (Stat)	Break	ct (Stat)	Break
CO2E	-4.518	2008	-4.220*	2020	-4.653	2000
TEXP	-3.081	2018	-3.754	2016	-4.328	2010
MNVA	-6.012***	2015	-3.595	1997	-4.961*	2015

Notes: The reported break date is endogenously determined. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

a broken trend with a unit root, with results presented in Table 3. For CO2E and TEXP, the null of a unit root with drift is not rejected under any specification, with all p-values above the conventional threshold of 5%, confirming their I(1) classification is robust to structural break allowance. For MNVA, the intercept specification rejects the null at the 1% level (statistic = −6.012, p = 0.0008) with a break identified at 2015, coinciding with post-Rana Plaza regulatory reforms and broader industrial policy shifts in Bangladesh's manufacturing sector. This structural shift is also visually apparent in the MNVA time-series plot presented in Figure A1. Since ZA rejection implies trend stationarity conditional on the break rather than a change in integration order, MNVA remains I(1), consistent with Table 2, and a step dummy D2015 is incorporated into the ARDL specification to isolate this structural shift from the long-run parameters.

The short-run ARDL(1,2,0) estimates, presented in Table 4, reveal that industrial carbon emissions exhibit significant own-period persistence, with the first lag of CO2E returning a coefficient of 0.402 (p=0.023), indicating that approximately 40 per cent of the previous period's emission level carries forward within the year. Among the textile export terms, contemporaneous TEXP and its first lag are individually insignificant, whereas the second lag, TEXP(-2), is positive and highly significant (coefficient = 0.387, p = 0.004), suggesting that the short-run emissions impact of export activity materialises with a two-period delay, consistent with the time required for capacity expansion and energy-intensive production scaling to follow export growth. MNVA exerts no discernible short-run influence on emissions (p = 0.913), and the structural break dummy D2015 is likewise insignificant at conventional levels (p = 0.335) in the short run, with its role in absorbing level shifts more relevant to the long-run relationship. The constant approaches but does not attain the 10% threshold (p = 0.061).

The bounds test for cointegration, presented in Table 5, evaluates the null hypothesis of no long-run relationship among the variables. The computed F-statistic of 5.6706 exceeds the upper bound critical value at the 5% significance level (5.473) but falls below the 1% threshold (7.873), providing evidence of cointegration at the 5% level. Similarly, the t-statistic of -3.682 surpasses the I(1) bound at 5% (-3.53) in absolute terms, corroborating the F-statistic inference. Both test statistics lie outside the inconclusive region between the I(0) and I(1) bounds, confirming the presence of a stable long-run equilibrium relationship between industrial carbon emissions, textile exports, and manufacturing value-added. This result validates the application of the ARDL framework and justifies

Table 4. ARDL short-run estimation

Variable	Coefficient	Std. Error	t-Statistic	Prob.
CO2E(-1)	0.4024	0.1645	2.4457	0.0229
TEXP	-0.0222	0.1405	-0.1583	0.8756
TEXP(-1)	0.0386	0.1518	0.2544	0.8015
TEXP(-2)	0.3869	0.1216	3.1814	0.0043
MNVA	-0.0393	0.3550	-0.1107	0.9129
D2015	0.0338	0.0343	0.9856	0.3350
C	-1.0301	0.5223	-1.9724	0.0613

Table 5. Bounds test for cointegration

		10% Bounds		5% Bounds		1% Bounds	
Test	Statistic	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)
F-statistic	5.6706	3.437	4.47	4.267	5.473	6.183	7.873
t-statistic	-3.682	-2.57	-3.21	-2.86	-3.53	-3.43	-4.1

Notes: I(0) and I(1) denote lower and upper bound critical values from Pesaran *et al*. (2001). Cointegration is supported when the test statistic exceeds the upper bound.

proceeding to estimate the long-run coefficients and error correction mechanism.

The long-run coefficient estimates, reported in Table 6, reveal the equilibrium relationship between the explanatory variables and industrial carbon emissions. Textile exports exert a positive and highly significant influence on emissions, with an estimated elasticity of 0.675 ($t = 6.343$, $p < 0.001$), indicating that a 1% increase in textile exports is associated with a 0.675% rise in industrial carbon emissions in the long run. This result underscores the carbon-intensive nature of Bangladesh's export-oriented textile sector and suggests that export expansion has been a substantial driver of industrial emissions over the study period. In contrast, manufacturing value-added fails to achieve statistical significance (coefficient = -0.066, $p = 0.941$), implying that broader manufacturing activity, when controlling for textile exports, does not exhibit a discernible long-run relationship with industrial emissions. The insignificance of MNVA likely reflects the dominant contribution of the textile sector to industrial emissions, such that variations in broader manufacturing value-added exert negligible marginal effects once textile exports are explicitly accounted for in the model.

The error correction model results, presented in Table 7, confirm the validity of the long-run relationship and quantify short-run adjustment dynamics. The error correction term is negative and highly significant (coefficient = -0.598, $p = 0.001$), indicating that approximately 60% of any deviation from long-run equilibrium is corrected within one year, which reflects a moderately rapid adjustment process. The long-run forcing variable TEXP(-1) retains its positive and significant coefficient (0.403, $p < 0.001$), consistent with the equilibrium estimates in Table 6. In the short run, the first lag of the change in textile exports, D(TEXP(-1)), exhibits a negative and significant coefficient (-0.387, $p = 0.049$), suggesting a temporary offsetting dynamic that dissipates as the system converges to equilibrium. The contemporaneous change in textile exports, manufacturing value-added, and the structural break dummy remain statistically

Table 6. Long-run estimation results

Variable	Coefficient	Std. Error	t-Statistic	Prob.
TEXP	0.6749	0.1064	6.3435	0.0000
MNVA	-0.0657	0.8778	-0.0749	0.9409

Notes: Long-run coefficients are derived from the ARDL model.

Table 7. Error Correction Model (ECM) results

Variable	Coefficient	Std. Error	t-Statistic	Prob.
ECT(-1)	-0.5976	0.1623	-3.6820	0.0013
TEXP(-1)	0.4033	0.1005	4.0113	0.0006
MNVA	-0.0393	0.5200	-0.0755	0.9405
D(TEXP)	-0.0222	0.1903	-0.1169	0.9080
D(TEXP(-1))	-0.3869	0.1856	-2.0842	0.0490
D2015	0.0338	0.0492	0.6878	0.4988
C	-1.0301	0.6162	-1.6718	0.1087

Table 8. Diagnostic test results

Test	Test Purpose	Statistic	Prob.
Breusch-Pagan-Godfrey	Heteroskedasticity	2.207	0.0811
Breusch-Godfrey LM	Serial correlation	0.0305	0.97
Jarque-Bera	Normality of residuals	0.7878	0.6744
Ramsey RESET	Functional form	1.7203	0.2038

insignificant, indicating that their influence operates primarily through the long-run channel rather than short-run fluctuations.

The diagnostic tests, summarised in Table 8, confirm the adequacy of the ARDL specification. The Breusch-Pagan-Godfrey test fails to reject the null hypothesis of homoscedastic errors at 5% (p = 0.081), indicating that variance remains constant across observations. The Breusch-Godfrey LM test yields no evidence of serial correlation in the residuals (p = 0.970), satisfying the assumption of independence. The Jarque-Bera statistic supports the normality of residuals (p = 0.674), while the Ramsey RESET test detects no functional form misspecification (p = 0.204). Additionally, the Cumulative Sum (CUSUM) and cumulative sum of squares (CUSUMSQ) plots presented in Figure 1 remain within the 5% critical bounds throughout the sample period, confirming parameter stability and the absence of structural instability. Collectively, these diagnostics validate the model's statistical integrity and support the reliability of the estimated coefficients.

To assess whether the estimated long-run relationship is sensitive to the choice of cointegration estimator, Table 9 reports robustness checks using Dynamic OLS (DOLS) and Fully Modified OLS (FMOLS). Both estimators confirm a positive and highly significant association between textile exports and industrial CO_2 emissions, with coefficient magnitudes that remain close to the ARDL estimate. By contrast, manufacturing value-added and the 2015 structural break dummy remain statistically insignificant across both specifications. The persistence of the export coefficient across alternative estimators strengthens the reliability of the main finding and indicates that the observed export-emissions nexus is not driven by model-specific estimation effects.

Granger causality reveals a statistically significant unidirectional causal flow from TEXP to CO2E (F = 7.942, p = 0.002), with the reverse direction unsupported (F = 0.471, p = 0.630), lending short-run directional support to the long-run elasticity reported in Table 6. CO2E Granger causes MNVA (F = 6.677, p = 0.005) but not vice versa (F = 0.093, p = 0.912), consistent with emissions accumulating ahead of measured manufacturing value-added as capacity-intensive production scales. TEXP similarly Granger causes MNVA (F = 6.451, p = 0.006), with no significant reverse effect (F = 0.917, p = 0.413). Collectively, the results in Table 10 position textile exports as the primary impulse variable within the

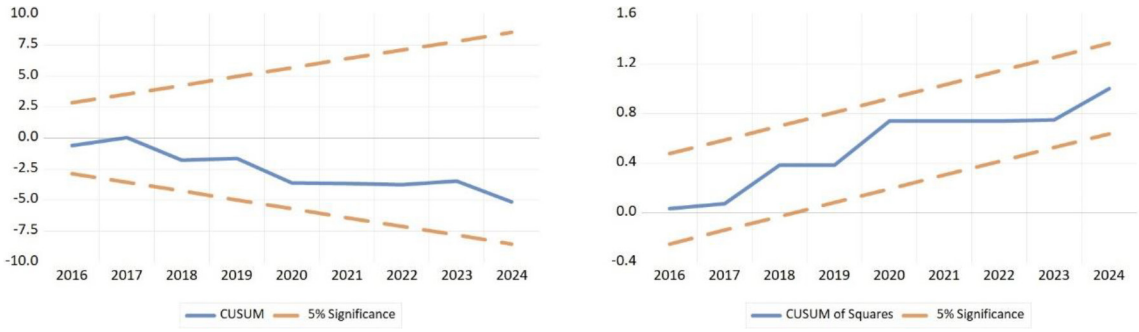


Figure 1. CUSUM and CUSUMSQ plots.

Table 9. Robustness checks using DOLS and FMOLS

	DOLS				FMOLS			
Variable	Coefficient	Std. Error	t-Stat	Prob.	Coefficient	Std. Error	t-Stat	Prob.
TEXP	0.5862	0.0855	6.8570	0.0000	0.6009	0.0553	10.8672	0.0000
MNVA	0.9250	1.1370	0.8136	0.4265	0.5094	0.4862	1.0477	0.3044
C	-2.5972	1.0702	-2.4267	0.0260	-2.2077	0.4638	-4.7599	0.0001
D2015	0.0074	0.1144	0.0650	0.9489	0.0773	0.0546	1.4142	0.1692

Table 10. Pairwise Granger causality test results

Direction of Causality	F-Statistic	Prob.	Decision	Conclusion
TEXP → CO2E	7.942	0.002***	Reject H_0	Unidirectional causality
CO2E → TEXP	0.471	0.63	Fail to Reject H_0	No causality
MNVA → CO2E	0.093	0.912	Fail to Reject H_0	No causality
CO2E → MNVA	6.677	0.005***	Reject H_0	Unidirectional causality
MNVA → TEXP	0.917	0.413	Fail to Reject H_0	No causality
TEXP → MNVA	6.451	0.006***	Reject H_0	Unidirectional causality

Notes: Pairwise Granger causality tests are estimated with two lags, consistent with the ARDL maximum lag order. *** denotes significance at the 1% level.

system, with industrial emissions and manufacturing value-added functioning as downstream outcomes rather than antecedent drivers.

4.2 Discussion

The estimated long-run elasticity of 0.675 confirms that export concentration in a carbon-intensive sector dominates Bangladesh's industrial emissions trajectory, favoring the pollution haven and composition-effect account over EKC-style convergence. This finding is particularly revealing given the insignificance of manufacturing value-added once textile exports are explicitly controlled, indicating that the textile sector's overwhelming contribution to industrial emissions overshadows broader manufacturing diversification. The result validates sectoral-level analysis over aggregate approaches in export-dependent economies, where a single dominant sector can determine environmental outcomes independently of overall manufacturing activity. The DOLS and FMOLS estimates corroborate this relationship, yielding coefficients of 0.586 and 0.601 respectively, confirming that the finding is robust across alternative cointegration estimators. The Granger causality results further establish that this relationship is unidirectional, running from TEXP to CO2E, corroborating the directional interpretation of the elasticity estimate and ruling out the possibility that emissions growth drives export expansion. These findings align with Khuky *et al.* (2022), who reported a positive export-emissions relationship using ARDL bounds testing for Bangladesh over 1983 to 2019. However, their study combined pre-1994 fiscal-year apparel data with calendar-year emissions series, introducing temporal misalignment in a dynamic model where lag structures are critical for identification. By restricting the analysis to the calendar-year series, this study provides cleaner identification of the long-run equilibrium relationship.

The positive textile export-emissions relationship operates through scale effects that dominate in the absence of compensating efficiency gains. As Ghazal *et al.* (2024) demonstrate, scale effects prevail when economies lack technological capacity for efficiency improvements. The textile sector's carbon intensity, accounting for 6 to 8 percent of global emissions (Sharpe *et al.*, 2022) and 67.8 percent of industrial zone emissions in Bangladesh (Biswas *et al.*, 2024), means export expansion directly scales carbon-intensive production. Unlike economies with diversified manufacturing where sectoral composition shifts can mitigate emissions (Shahzad *et al.*, 2020), Bangladesh's export concentration in a single high-emission sector precludes composition effects from offsetting scale. Huang *et al.* (2026) identify electricity consumption as the primary driver of textile emissions, establishing the direct mechanism linking export growth to industrial carbon output. The two-period lag in short-run dynamics reflects capacity expansion timelines characteristic of capital-intensive manufacturing. Export orders trigger investment in machinery and infrastructure, with energy-intensive production scaling materialising only after an investment gestation period. This pattern aligns with Jeon (2023), who models time-to-build lags wherein industrial capacity expansion and subsequent energy consumption emerge following initial investment commitments. The lagged structure implies that emissions impacts of export growth are not immediately reversible even under demand shifts, as installed capacity remains operative beyond the business cycle.

The insignificance of manufacturing value-added, once textile exports are controlled, does not contradict broader manufacturing-emissions literature but rather reveals sectoral dominance. When the primary emitting subsector is explicitly modeled, residual variation in aggregate manufacturing contributes no explanatory power. This result is consistent with Wu *et al.* (2025), who document substantial sectoral heterogeneity in emissions responses, validating disaggregated analysis in export-concentrated economies. The error correction coefficient of -0.598 indicates moderately rapid adjustment, with approximately 60 percent of deviations from equilibrium corrected annually. This adjustment speed is comparable to Kadioglu *et al.* (2025), who report -0.757 for Turkey's green economy transition. The 2015 structural break identified in manufacturing value-added coincides with post-Rana Plaza regulatory reforms, though the break appears in aggregate manufacturing rather than emissions or exports, suggesting broader industrial policy shifts rather than emissions-specific interventions.

The findings appear to diverge from Zhou *et al.* (2022), who identify emissions reductions from global value chain embedment through technology transfer mechanisms. However, Bangladesh's textile sector operates primarily in cut-make-trim segments with limited backward linkages. Sampath and Vallejo (2018) demonstrate that embedment in low-technology GVC segments yields limited technological upgrading. Position within value chains matters: low-complexity segments lack the efficiency channels identified by Zhou *et al.*, rendering the findings complementary rather than contradictory.

Several limitations warrant acknowledgment. Aggregate industrial combustion emissions do not isolate textile-specific emissions, though Biswas *et al.* (2024) provide sectoral validation. ARDL assumes linear relationships; threshold effects documented by Bakri *et al.* (2025) might exist but remain undetectable in small samples. The Zivot-Andrews procedure identifies single breaks; multiple structural changes may exist beyond the capacity of 29 observations. Nevertheless, the findings carry direct implications for decarbonisation pathways in export-dependent economies, where sectoral concentration shapes the design of targeted interventions over economy-wide approaches.

4.3 Policy Implications

The findings motivate a three-tiered policy framework spanning green finance architecture, sustainable sourcing architecture, and factory-level technology architecture. While the empirical analysis is grounded in Bangladesh's specific institutional and export context, the framework's logic extends to any economy where export concentration in a carbon-intensive manufacturing sector drives aggregate industrial emissions, including Vietnam, Cambodia, and Pakistan, where analogous structural dependencies prevail.

Tier I addresses the supply-side financing constraint. The empirical finding that a 1 percent increase in textile exports raises industrial carbon emissions by 0.675 percent in the long run, combined with the absence of autonomous efficiency gains at the sectoral level, establishes a clear case for supply-side financial intervention. Achieving a 50 percent reduction in greenhouse gas emissions by 2030 requires an estimated investment of US$6.6 billion, against which confirmed funding of approximately US$1.6 billion leaves a financing gap of US$4.8 billion (Apparel Impact Institute, 2025). Three policy levers address this gap. First, Bangladesh Bank's Green Transformation Fund should ring-fence a dedicated dyeing-and-finishing tranche, extending preferential refinancing below the current 5 percent benchmark to factories adopting low-liquor-ratio or closed-loop systems. While existing concessional infrastructure already offers rates well below the prevailing market rate of over 10 percent (The Business Standard, 2025), green banking uptake in Bangladesh remains comparatively limited, underscoring the need for more targeted regulatory design (Rahman *et al.*, 2023). Second, while large exporters already access GCF-IDCOL concessional lines, a blended finance co-investment vehicle pairing multilateral first-loss capital with domestic commercial lending should target mid-tier and SME factories, which face structural barriers to green finance access (Ali *et al.*, 2026). The Apparel Impact Institute's proposed US$250 million Fashion Climate

Fund offers a replicable structure for this vehicle. Third, the government's cash incentive scheme for textile exporters should incorporate a carbon intensity threshold, creating a direct fiscal signal linking export competitiveness to verified emissions performance.

Tier II converts buyer-side regulatory pressure into a structured domestic demand signal. The paper's finding that textile exports, rather than aggregate manufacturing activity, drive Bangladesh's industrial emissions trajectory implies that demand-side regulatory pressure operates through precisely the channel most consequential for environmental outcomes. With the sector accounting for 84.58 percent of total export earnings and approximately 45 percent of RMG exports destined for the EU, the industry's exposure to sustainability-linked trade barriers is not a peripheral compliance concern but a structural economic risk (Khatun *et al.*, 2023). Bangladesh's 2026 graduation from least developed country status will extinguish Duty Free Quota Free access, making qualification for GSP+, which carries explicit environmental conditionality, a commercial necessity rather than a policy aspiration. Three policy levers translate this external pressure into a structured domestic demand signal. First, all factories exporting above a defined threshold should be required to disclose Scope 1 emissions and water intensity in a standardized format compatible with EU Ecodesign for Sustainable Products Regulation Digital Product Passport (DPP) requirements, positioning the sector ahead of the 2029 compliance window (Carvalho *et al.*, 2025). The DPP framework consolidates dispersed lifecycle data into actionable, buyer-readable intelligence, directly reducing the verification burden on sourcing firms. Second, BGMEA, in coordination with the Department of Environment, should administer a tiered factory registry classifying exporters by emissions performance, with preferential customs and audit treatment incentivizing buyers to concentrate sourcing in higher-performing tiers. Third, Bangladesh should formalize bilateral sustainability compacts that anchor tariff preference commitments to verified sector-level emission intensity improvements, embedding the domestic green finance architecture of Tier I within a durable geopolitical framework.

Tier III targets the process-level emissions source identified in the literature. Life cycle assessment evidence from Bangladesh's textile manufacturing confirms that the dyeing and finishing stage is the single largest contributor to global warming potential, accounting for 38.36 percent of total emissions across the cotton polo shirt production chain (Islam *et al.*, 2024), a finding consistent with broader cross-study evidence that wet processing stages dominate over assembly operations (Dominish & Sharpe, 2021). This sectoral concentration of emissions in one identifiable process stage creates a precise target for technology-specific policy intervention. Three policy levers operationalize this targeting. First, Bangladesh should publish a Ministry of Commerce Approved Technology List covering low-emission dyeing and finishing processes, with machinery on the list attracting zero import duty and automatic eligibility for Green Transformation Fund financing. The short-run ARDL estimates in the paper document a two-period investment gestation lag between export growth and emissions realisation, indicating that reducing the upfront cost barrier to technology adoption is critical for accelerating the transition timeline. Second, combined single-bath pretreatment and dyeing processes, which consolidate multiple water- and energy-intensive stages into one cycle, should be formally certified by the Bangladesh Standards and Testing Institution. Certified factories receive priority access to green finance and green-tier registration under the Tier II factory registry. Low-liquor-ratio reactive dyeing at optimized ratios reduces energy consumption by approximately 34 to 38 percent relative to conventional processes (Abeer *et al.*, 2026), while supercritical fluid dyeing eliminates water and effluent generation entirely, though scalability constraints currently limit deployment (De Oliveira *et al.*, 2023; Hussain & Wahab, 2018). Third, factories adopting spray or foam-based finishing technologies should receive time-limited accelerated depreciation allowances, directly shortening payback periods and addressing the capital cost barrier that disproportionately constrains smaller producers.

5. Conclusion

This study examined whether Bangladesh's textile export expansion, rather than manufacturing activity

broadly, drives the country's rising industrial carbon emissions. The evidence points clearly in one direction: emissions growth in Bangladesh's industrial sector is tied specifically to the expansion of textile exports, not to manufacturing growth more broadly, and the direction of influence runs from exports to emissions rather than the reverse. This confirms that the carbon footprint of Bangladesh's industrialisation is concentrated in its dominant export sector, and that policies aimed at manufacturing in general are unlikely to address the primary source of emissions growth.

The novelty of this study lies in its sectoral focus and methodological care. While prior research on Bangladesh's trade-emissions relationship has largely treated manufacturing as a single aggregate category, this study isolates the textile sector's distinct contribution, revealing a channel that aggregate analysis conceals. It also resolves a data inconsistency in earlier work by aligning textile exports on a uniform calendar-year basis and accounts for a structural shift in manufacturing that could otherwise distort the results. The resulting framework offers a transferable model for other textile-dependent exporters, such as Vietnam, Cambodia, and Pakistan. Certain limitations remain. The emissions measure used reflects industrial combustion broadly rather than textile-specific output, the analysis assumes a linear relationship between exports and emissions, and only a single structural break could be examined given the sample length. Future research extending this work through sector-specific emissions data, nonlinear modeling, and cross-country comparisons would deepen and generalize these findings. Disaggregating emissions by production stage would help pinpoint where interventions yield the greatest returns, while panel-based extensions to other textile-dependent exporters would test the elasticity's broader applicability.

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Author Contributions

All authors jointly contributed to the conceptualisation of this study. Tahsin Shabab Rajee supervised the research and led the study design, methodology, and econometric analysis, conducted using Python and EViews 13, along with interpretation of the findings. Sinthia Tasnim developed the introduction and literature review. Hafsa Binte Karim Benoy contributed to data collection and led the discussion and policy implications sections. Md. Abid Hasan contributed to data collection and drafted the abstract and conclusion, and proofread the manuscript.

Annexure

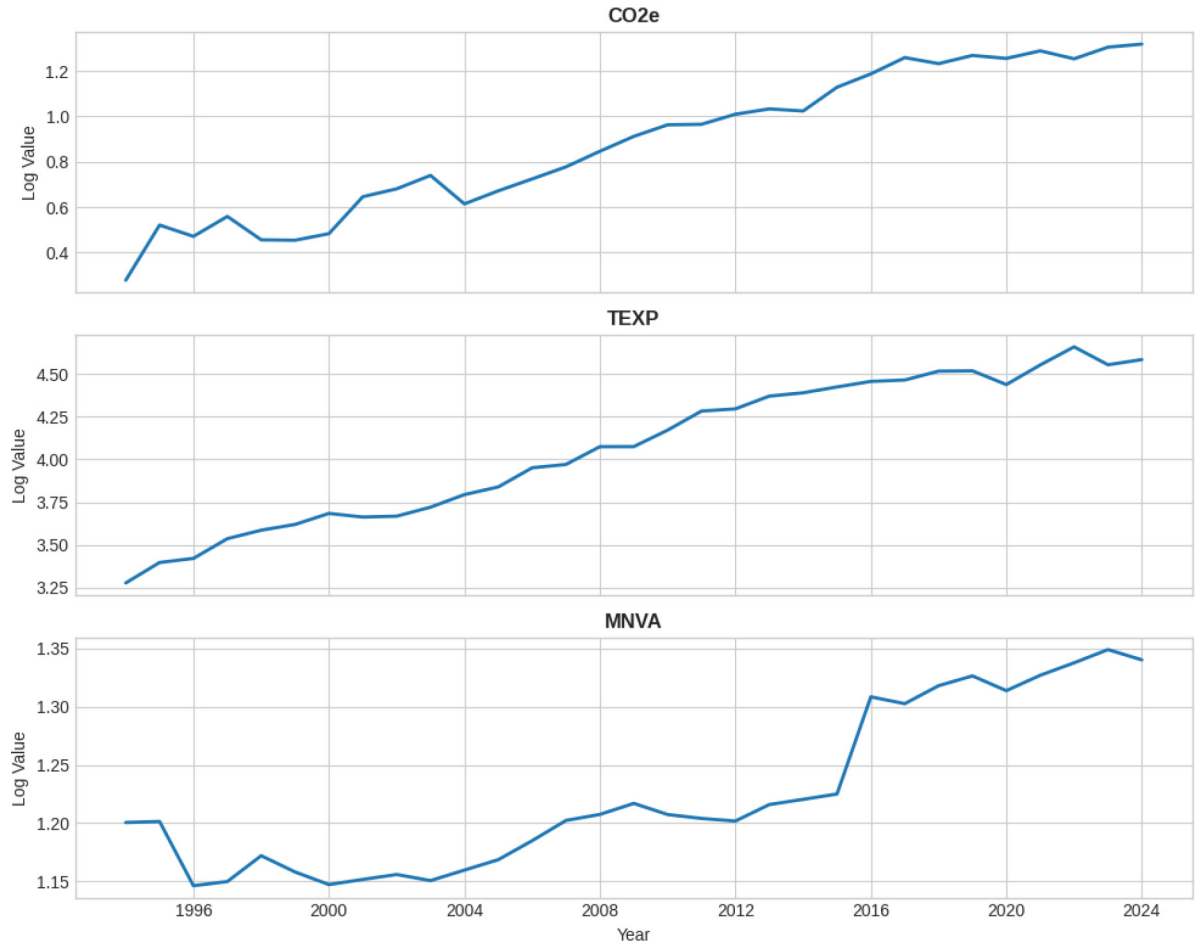


Figure A1. time-series plots.