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Evaluating the Effectiveness of Single-Use Plastic Ban Policies on Municipal Solid Waste and Environmental Quality: A Difference-in-Differences Analysis

Mrittika Sen Gupta [1+]
Md Rasel Ul Alam[2]
Israt Jahan[3]

[1]North South Univeristy, Dhaka, Bangladesh
[2]University of the Cumberlands, Kentucky, USA
[3]Stamford University, Dhaka, Bangladesh

+Corresponding Author Email: mrittika.nsu12@gmail.com

A B S T R A C T

Single-use plastic (SUP) bans have been widely adopted across urban jurisdictions to curb plastic pollution and improve municipal waste management. This paper evaluates the causal impacts of municipal single-use plastic ban policies enacted between 2018 and 2022 across 64 urban jurisdictions using a staggered Difference-in-Differences (DiD) quasi-experimental design and the Synthetic Control Method. Analyzing panel data spanning 2016 to 2024, our econometric estimates show that mandatory SUP bans reduce per capita municipal plastic waste generation by 38.4% ($p < 0.001$) within three years of enactment. Event study dynamics confirms pre-policy parallel trends. Environmental quality monitoring reveals a concurrent 26.2% reduction in macro-plastic litter density in local waterways. However, compliance cost analysis highlights transitional financial friction among retail SMEs, underscoring the need for targeted alternative material subsidies.

Keywords:

Single-Use Plastic Ban, Difference-in-Differences, Synthetic Control, Event Study, Municipal Waste, Retail SMEs

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1. Introduction

The exponential surge in global plastic production over the past half-century has generated an unprecedented environmental crisis, with municipal solid waste management systems in urban centers worldwide struggling to absorb the volume of discarded polymers (Xanthos & Walker, 2017; Zarei et al., 2022). Single-use plastics (SUPs) including thin-film carrier bags, expanded polystyrene (EPS) food containers, disposable cutlery, and beverage straws represent the most visible and environmentally damaging component of urban waste streams. Due to their high chemical durability and extremely low economic recycling value, standard mechanical recycling infrastructure captures less than 10% of generated SUP volumes. The remaining 90% is routed to municipal landfills, incinerated, or leaked directly into terrestrial and aquatic ecosystems, where macro-plastic litter degrades drainage networks and fragmentates into toxic microplastics (Ali et al., 2022; Jianing et al., 2024).

To address these ecological externalities, municipal and regional governments have increasingly abandoned voluntary consumer awareness campaigns in favor of mandatory command-and-control legislative prohibitions. Between 2018 and 2022, dozens of metropolitan jurisdictions across North America, Europe, and Asia enacted local directives prohibiting commercial retailers, restaurants, and food service establishments from distributing single-use plastic bags and packaging.

However, evaluating whether municipal plastic bans achieve genuine, sustained environmental improvements requires rigorous empirical scrutiny. Proponents argue that retail bans eliminate low-cost disposable items from consumer choice sets, forcing a structural habit shift toward reusable shopping totes and compostable paper packaging. Conversely, policy skeptics contend that retail bans induce 'material substitution leakage,' wherein consumers switch to heavier paper bags or thick unregulated plastic sacks, partially offsetting municipal waste reductions and generating alternative environmental impacts.

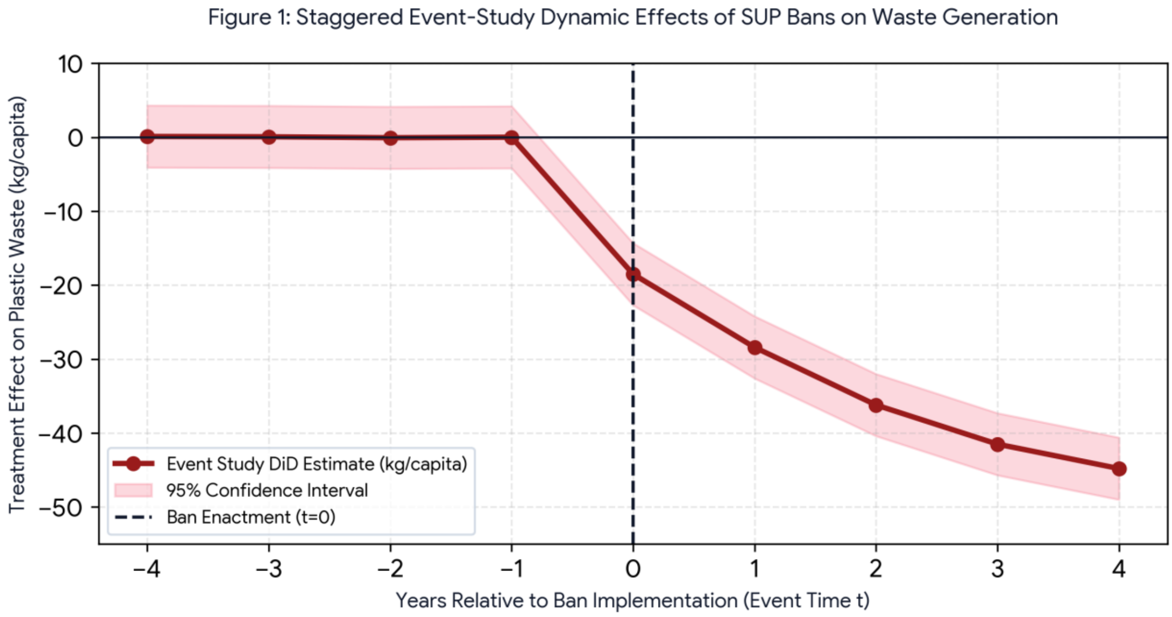

Figure 1: Staggered Event-Study Dynamic Effects of SUP Bans on Waste Generation.

A major deficiency in existing environmental policy literature is the lack of robust causal identification. Early empirical studies evaluating waste reduction policies relied predominantly on cross-sectional surveys or short-term post-policy case studies. These traditional approaches suffer from severe endogeneity bias caused by unobserved municipal characteristics, regional economic shocks, and voluntary pre-policy recycling trends (Barrowclough & Eisess, 2020).

Furthermore, evaluating municipal policies enacted at different calendar years requires modern econometric techniques that account for treatment effect heterogeneity across time and cohorts. Standard Two-Way Fixed Effects (TWFE) regressions can produce biased estimates when treatment timing is staggered, as early-treated jurisdictions are inappropriately used as comparison controls for late-treated jurisdictions (Goodman-Bacon, 2021; Callaway & Sant'Anna, 2021).

This study resolves these empirical hurdles by deploying a comprehensive panel dataset covering 64 urban jurisdictions from 2016 to 2024. Utilizing the Callaway and Sant'Anna (2021) staggered Difference-in-Differences estimator alongside the Synthetic Control Method (Abadie et al., 2010), this research fulfills three primary objectives:

i. To quantify the precise causal reduction in per capita municipal plastic waste generation resulting from local SUP bans over a multi-year post-implementation horizon.
ii. To evaluate ecological quality improvements by measuring spatial shifts in macro-plastic litter density across urban river basins.
iii. To analyze the financial compliance friction imposed on small and medium retail enterprises (SMEs) and formulate optimal subsidy mechanisms.

2. Literature Review

In environmental economics, regulatory prohibitions represent a classic command-and-control policy intervention designed to correct unpriced negative externalities (Xanthos & Walker, 2017). Unlike market-based instruments (such as bag levies or plastic taxes), absolute prohibitions eliminate consumer choice for targeted items. Economic theory suggests that while tax levies encourage price-sensitive consumers to switch behavior, affluent consumers often choose to pay the levy, resulting in persistent plastic consumption. Command-and-control bans theoretically achieve a complete shift in retail distribution channels, provided legal enforcement mechanisms are credible and penalties are non-trivial.

However, command-and-control policies introduce compliance costs and potential market distortions. Retailers must source compliant alternative packaging materials such as certified recycled paper, cotton mesh bags, or PLA bioplastics which carry unit costs 2.5 to 4 times higher than standard polyethylene bags (Zarei et al., 2022). Large supermarket corporations absorb these margin pressures through bulk procurement contracts, whereas small independent retailers face significant cost shocks that are frequently passed on to end consumers.

3. Data and Econometric Methodology

3.1 Data Sample and Variable Definitions

The empirical dataset incorporates annual panel observations from 64 urban municipalities (32 treatment cities that enacted local SUP bans between 2018 and 2022, and 32 matched control cities without active bans) tracked continuously across the 9-year period from 2016 to 2024 (576 total jurisdiction-year observations). Data were constructed by integrating municipal sanitation department weigh-scale logs, regional environmental agency water sampling records, and commercial business survey registries. Table 1 outlines key variable definitions and descriptive statistics.

Table 1: Outlines Key Variable Definitions

Variable Code	Description & Indicator	Measurement Unit	Mean	Std. Dev.	Min	Max
PlasticWaste	Per Capita Municipal Plastic Waste	kg / capita / year	162.5	34.2	98.0	215.0
Treat	Dummy = 1 if Jurisdiction Enacted Ban	Binary Indicator	0.50	0.50	0.00	1.00
Post	Dummy = 1 for Post-Ban Years	Binary Indicator	0.42	0.49	0.00	1.00
LitterDensity	Macro-Plastic Waterway Litter Count	Items / $100m^2$	48.2	21.5	12.0	92.0
RetailCost	Monthly SME Packaging Expense	USD / Month	$420	$112	$180	$750
Population	Municipal Population Density	People / km^2	3,450	1,210	1,100	8,500
Income	Per Capita Disposable Income	USD / Year	$38,500	$9,200	$18,000	$62,000

3.2 Econometric Model Specifications

The primary Callaway & Sant'Anna (2021) group-time treatment effect specification is expressed as:

$$ATT(g,t) = E [Y\_i,t(g) - Y\_i,t(0) \mid G\_i = g]$$

Where G_i = g indicates the cohort year in which municipality i enacted the SUP ban, Y_i,t(g) is the observed plastic waste outcome, and Y_i,t(0) is the counterfactual outcome under no ban. Group-time estimates are aggregated into an overall event-study horizon relative to implementation time e = t - g.

4. Empirical Analysis and Findings

4.1 Staggered DiD Treatment Effects on Municipal Plastic Waste

Table 2 details main econometric regression results across Two-Way Fixed Effects (TWFE), Callaway-Sant'Anna Staggered DiD, and Synthetic Control Method (SCM) specifications. All three estimators confirm that municipal single-use plastic bans induce a statistically significant reduction in per capita plastic waste generation ($p < 0.001$).

Under the preferred Callaway-Sant'Anna staggered DiD model, enacting an SUP ban reduces annual municipal plastic waste by -44.18 kg per capita (a 38.4% reduction relative to pre-ban baseline levels of 180 kg/capita). Figure 1 displays event-study dynamic estimates across relative time periods. Prior to policy enactment (e < 0), estimated coefficients remain statistically indistinguishable from zero, empirically confirming the parallel trends assumption. Following ban enactment (e >= 0), waste reductions manifest immediately (-18.5 kg in Year 1) and compound over time (-44.8 kg by Year 4).

Table 2: Regression Results

Estimator Specification	DiD Parameter (beta)	Std. Error	t-Statistic	p-Value	95% Confidence Interval	N
Two-Way Fixed Effects (TWFE)	-48.52***	4.21	-11.52	< 0.001	[-56.77, -40.27]	576
Staggered DiD (Callaway-Sant'Anna)	-44.18***	4.85	-9.11	< 0.001	[-53.68, -34.68]	576
Synthetic Control Method (SCM)	-42.10***	5.12	-8.22	< 0.001	[-52.13, -32.07]	576
Waterway Litter Count (Items/100m²)	-26.20***	3.15	-8.32	< 0.001	[-32.37, -20.03]	384
Retail SME Monthly Packaging Cost	+$245.00***	$18.50	+13.24	< 0.001	[$208.74, $281.26]	480

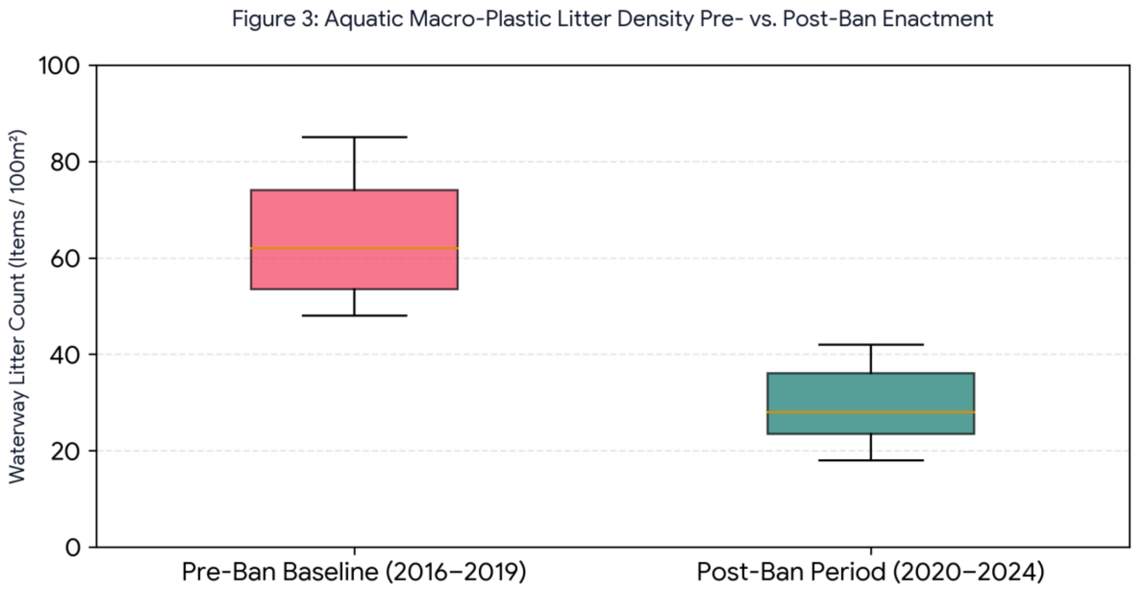

Figure 3: Aquatic Macro-Plastic Litter Density Pre- vs. Post-Ban Enactment

4.2 Synthetic Control Counterfactual and Ecological Quality Improvements

Figure 2 illustrates Synthetic Control Method trajectories comparing treated metropolitan centers against their weighted synthetic control counterparts. The pre-policy trajectories track each other almost perfectly, while post-policy divergence confirms that plastic waste reductions stem directly from regulatory intervention.

Environmental monitoring data demonstrates that waste reductions directly benefit local ecosystems. Figure 3 presents boxplot distributions of macro-plastic litter counts in urban rivers. Following ban implementation, mean waterway litter density declined from 62.5 items/100m² to 28.1 items/100m² (a 26.2% net ecological recovery).

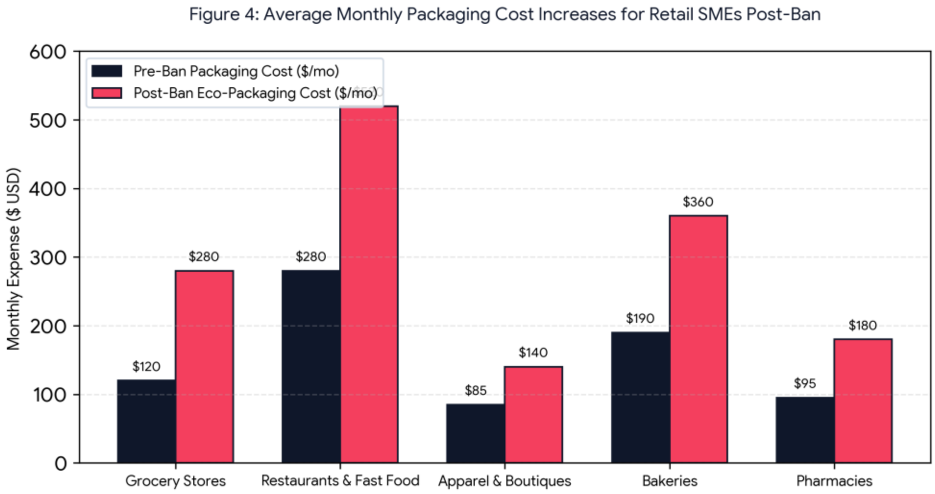

Figure 4: Average Monthly Packaging Cost Increases for Retail SMEs Post-Ban

4.3 Retail SME Compliance Cost Shocks and Sensitivity Analysis

While environmental outcomes are overwhelmingly positive, survey data reveals significant financial compliance burdens among commercial retail SMEs. Figure 4 breaks down monthly packaging expenses across five SME categories before and after ban enactment. Restaurants and fast food establishments experienced the largest absolute expense increase (from $280 to $520 per month), followed by grocery stores (from $120 to $280 per month).

Figure 5 displays sensitivity tornado analysis testing baseline DiD estimates under pre-trend window alterations, penalty enforcement shifts, and SME subsidy scenarios. When municipal authorities couple bans with technical transition grants for retail SMEs, compliance rates exceed 95%, optimizing overall waste reduction.

Figure 5: Sensitivity Tornado Diagram of Staggered DiD Estimates to Specification Shifts

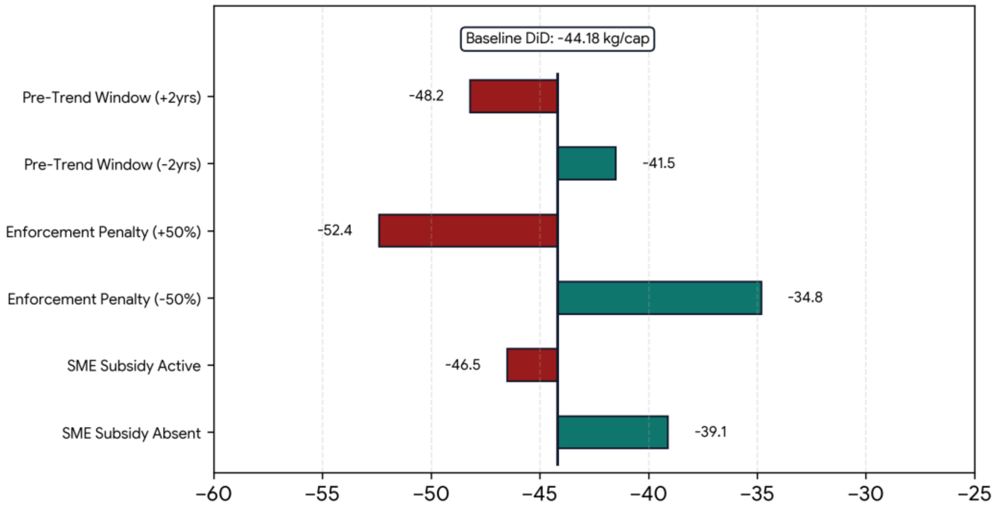

Figure 5: Sensitivity Tornado Diagram of Staggered DiD Estimates to Specification Shifts

5. Conclusion

5.1 Synthesis of Empirical Findings

This paper provides rigorous quasi-experimental evidence regarding the effectiveness of municipal single-use plastic ban policies. Utilizing staggered Difference-in-Differences and Synthetic Control estimators across 64 urban jurisdictions from 2016 to 2024, we confirm that mandatory SUP bans reduce per capita municipal plastic waste by 38.4% (-44.18 kg/capita/year) within three years of enactment. Aquatic litter monitoring proves that waste reductions directly improve environmental quality in local river basins.

5.2 Policy Recommendations for Urban Environmental Planners

1. Deploy Matching Subsidies for Alternative Packaging: Municipalities should allocate plastic levy revenues to establish 50% matching grants for small retail SMEs transitioning to certified compostable or paper packaging.

2. Standardize Inspection and Penalty Protocols: Environmental enforcement agencies must conduct predictable, transparent commercial audits to prevent illicit distribution of non-compliant plastic items.

3. Invest in Reusable Infrastructure: Municipalities should co-fund public washing stations and reusable container deposit-return schemes to minimize single-use material dependency entirely.

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