Supplementary Material (SM)

Uncertainty Characterization

Formal Uncertainty Analysis

From this study, the dominant uncertainties are:

- Tyre lifetime (replacement frequency: 2–3 years)
- Tyre mass (cars 9 kg, buses 45 kg, trucks 60 kg)
- Chemical concentrations: CPs: 13–67 mg/kg; 6PPD: 100–4000 mg/kg; PAHs: 17–357 mg/kg
- Tyre wear rate (mass loss per tyre)

The scenarios are converted into formal uncertainty bounds as follows: Lower bound (optimistic); Central estimate (most plausible); Upper bound (worst case).

Therefore, the uncertainty range ratio (orders of magnitude) is presented as:

CP stock: 267–1375 t → factor ≈ 5.1
6PPD: 2053–82,148 t → factor ≈ 40
PAHs: 349–7332 t → factor ≈ 21

Relative uncertainty or relative range (%)

$$\text{Relative uncertainty} = \frac{High - Low}{Mid}$$

The result is presented in Table S1.

Table S1. Relative uncertainty.

Parameter	Low	Mid	High	Relative Uncertainty
CP stock	267	821	1375	1.35 (135%)
6PPD stock	2053	11,726	82,148	6.83 (683%)
PAHs stock	349	3840	7332	1.82 (182%)
TPM	1,095,144	1,644,969	2,554,307	0.89 (89%)
CP release	14.2	92.6	171	1.69 (169%)
6PPD release	110	5163	10,216	1.96 (196%)
PAH release	18	464.5	911	1.92 (192%)

Relative uncertainty values range from 0.89 (TPM) to 6.83 (6PPD stock), indicating that uncertainty is particularly high for parameters with poorly constrained concentration ranges (e.g., 6PPD), while bulk physical estimates such as tyre mass loss are comparatively more robust.

Uncertainty Analysis Using Monte Carlo Simulation

A Monte Carlo simulation (n = 10,000) was performed (Table S2) to quantify uncertainty in the estimation of CP stocks in tyres. CP concentrations were represented using a uniform distribution (13–67 mg/kg), reflecting reported literature ranges.

Table S2. Monte Carlo Results (CP stock in tyres).

Statistic	Value (t)
Mean	821 t
Median	818 t
5th percentile	~320 t
95th percentile	~1320 t
Minimum	267 t
Maximum	1376 t

The simulation produced a mean estimate of approximately 821 t, consistent with the deterministic midpoint. The 5th–95th percentile range (≈320–1320 t) captures the most probable uncertainty interval, while the full range (267–1375 t) represents extreme boundary conditions. The relatively symmetric distribution indicates that model outputs are not driven by extreme parameter values but reflect proportional propagation of input uncertainty.

The Monte Carlo results demonstrate that while the full uncertainty range spans approximately a factor of five, the most probable values fall within a narrower band. This confirms that the wide ranges reported in the deterministic analysis are not artefacts of model instability, but rather reflect realistic variability in input parameters, particularly chemical concentrations.

One-at-a-Time (OAT) Sensitivity Analysis

We varied one parameter by ±20%, keeping others constant, and observed the effect on output.

Sensitivity coefficient (S):

$$S = \frac{\%\ \text{change in output}}{\%\ \text{change in input}}$$

The results are presented in the Table S3.

Table S3. Sensitivity Ranking.

Parameter	Sensitivity (S)	Influence
6PPD concentration	~1.0	Very High
CP concentration	~1.0	Very High
PAHs concentration	~1.0	Very High
Tyre wear rate	~1.0	Very High
Replacement frequency	~1.2	Very High
Tyre mass	~1.0	High
Fleet composition	0.3–0.6	Moderate–Low

Sensitivity analysis indicates that model outputs are most strongly influenced by tyre wear rates, replacement frequency, and additive concentrations, all of which exhibit near-linear relationships with estimated emissions ($S \approx 1$). In contrast, fleet composition and tyre configuration assumptions have comparatively lower influence ($S \approx 0.3–0.6$).

These findings demonstrate that the wide range of reported results is primarily driven by uncertainty in key input parameters rather than model instability. In particular, chemical composition (e.g., 6PPD concentration spanning two orders of magnitude) represents the dominant source of uncertainty. Improving empirical data on tyre wear rates and additive concentrations would significantly reduce uncertainty in future assessments.

The sensitivity analysis confirms that the model behaves predictably and proportionally, with no evidence of numerical artefacts. The large output ranges reflect real-world variability in tyre composition and usage rather than weaknesses in the modelling approach.

Systematic Exploration of Assumptions

In this study, the critical assumptions are: Tyre replacement frequency; Tyre wear rate (mass loss); Chemical concentrations (CPs, 6PPD, PAHs); Tyre mass (vehicle type); Fleet composition (cars/buses/trucks).

For tyre replacement frequency, the assumptions are: cars: 3 years; buses/trucks: 2 years and alternative scenarios given in Table S4.

Table S4. Alternative scenarios.

Scenario	Replacement interval	Effect
Conservative	+20% longer life (3.6 yrs)	↓ tyres used
Base case	3 yrs	Baseline
High turnover	−20% (2.4 yrs)	↑ tyres used

Quantitative implication is calculated as:

Number of replacements (N):

$$N = \frac{Time}{Lifetime}$$

So:

3 → 2.4 yrs = +25% increase in replacements

3 → 3.6 yrs = −17% decrease

This impacts waste tyres, TPM, and chemical emissions. All increase proportionally (~±20–25%).

Shorter tyre lifetimes (e.g., due to poor road conditions or use of second-hand tyres) can increase total tyre turnover and associated emissions by approximately 25%, highlighting the importance of maintenance practices and import quality controls.

For tyre wear rate, the data are: Low (1.1 million t); High (2.55 million t); Factor ≈ 2.3×

The implication is that since: $Emission \propto Wear\ Rate$.

Then: CP release: 14 → 171 t; PAHs: 18 → 911 t ; 6PPD: 110 → 10,216 t

Tyre wear rate is the dominant driver of emission variability. A twofold increase in wear rate results in a proportional increase in pollutant release, indicating that driving conditions, road quality, and vehicle load are critical determinants of environmental impact.

For chemical concentration assumptions (example: 6PPD): Low: 100 mg/kg; High: 4000 mg/kg; 40× difference; the result output: 2053 t → 82,148 t; also ~40× increase. The assumed concentration of additives, particularly 6PPD, introduces the largest uncertainty, with output estimates varying by up to two orders of magnitude. This reflects real variability in tyre formulations rather than model instability.

Tyre Mass Assumptions: the assumptions are: cars: 9 kg; buses: 45 kg; trucks: 60 kg. If mass increases by 20%, total chemical stock increases by 20%. Tyre mass assumptions moderately influence results; however, compared to wear rates and chemical composition, their contribution to overall uncertainty is smaller.

Fleet Composition: the assumptions are: cars: 70%; buses: 29%; trucks: 1%. If trucks increase from 1% → 3%. total tyre count changes slightly, but mass increases significantly (heavy tyres). The implication is higher emissions (especially CPs, PAHs). Changes in fleet composition, particularly increases in heavy-duty vehicles, can disproportionately increase pollutant emissions due to higher tyre mass and wear rates per vehicle.

In summary (Table S5), systematic exploration of model assumptions demonstrates that output variability is primarily driven by three key factors: tyre wear rates, chemical composition, and replacement frequency. While parameters such as tyre mass and fleet composition contribute to uncertainty, their effects are comparatively smaller. Importantly, the relationships between assumptions and outputs are largely linear and predictable, confirming that the wide result ranges reflect real-world variability rather than artefacts of the modelling approach.

Table S5. Systematic exploration of assumptions.

Assumption	Range Tested	Effect on Output	Importance
Replacement frequency	±20%	±20–25%	High
Wear rate	1.1–2.55 Mt	~2.3×	Very High
6PPD concentration	100–4000 mg/kg	~40×	Extremely High
CP concentration	13–67 mg/kg	~5×	High
Tyre mass	±20%	±20%	Moderate
Fleet composition	realistic variation	<2×	Moderate–Low

The systematic exploration confirms that the model behaves consistently across a wide range of plausible assumptions. The observed variability in results is therefore a reflection of real uncertainty in system parameters—particularly tyre chemistry and wear behaviour—rather than a limitation of the modelling framework.

Validation Against Independent Data

Since direct national measurements are scarce, we validate by: cross-comparison with literature ranges; scaling against global/regional estimates; consistency checks with independent reports. This is standard practice in MFA studies. We validated: tyre consumption/waste generation; TPM emissions; CPs, 6PPD, PAHs estimates.

In this study, for tyre consumption and waste we observed ~776 million tyres (1980–2020); ≈ 19 million tyres/year. The estimated annual waste tyre generation of approximately 19 million units is consistent with independent national reports indicating ~20 million tyres per year, demonstrating strong agreement (within error ~5%) and supporting the validity of the model outputs.

Validation of TPM emissions: In this study, 1.1–2.55 million tonnes over 40 years → ≈ 27,000–64,000 t/year; compared with global benchmarks: global tyre wear: ~6–10 million tonnes/year; Nigeria = ~1–2% of global fleet (reasonable estimate).

Scaling check: Nigeria expected ≈1%×6–10 million = 60,000–100,000 t/year; the estimate in this study is 27,000–64,000 t/year, slightly lower but same order of magnitude. This is plausible given lower vehicle mileage in Nigeria and traffic congestion (less high-speed wear). The estimated annual tyre wear emissions (27,000–64,000 t/year) fall within the same order of magnitude as scaled global estimates, which suggest tens of thousands of tonnes annually for countries with comparable fleet sizes. This supports the plausibility of the model outputs.

Validation of Chemical Concentrations: The literature ranges we used are: CPs: 13–67 mg/kg; 6PPD: 100–4000 mg/kg; PAHs: 17–357 mg/kg. These are already independent datasets, so validation = consistency with literature. The concentration ranges used for CPs, 6PPD, and PAHs are derived from multiple independent experimental studies and fall within widely reported values for tyre rubber, supporting the validity of the input parameters.

Validation of Relative Contribution: From this study, tyres contribute 0.1–5% of CP imports. It is not dominant source (realistic) and consistent with global findings. The estimated contribution of tyres to national CP inflows (0.1–5%) aligns with international assessments that identify tyres as a secondary but non-negligible source of chlorinated paraffins.

Internal Consistency Check: Internal validation shows consistent scaling relationships across the model: higher tyre wear scenarios result in proportionally higher emissions, and heavy-duty vehicles consistently contribute larger pollutant loads due to higher tyre mass and wear rates. These patterns are consistent with established literature.

In summary, model validation was conducted through comparison with independent datasets, literature benchmarks, and internal consistency checks. The estimated annual waste tyre generation (~19 million units) closely matches national reports (~20 million units), indicating strong agreement. Tyre wear emissions fall within the expected order of magnitude when scaled against global estimates, supporting their plausibility. Furthermore, input parameters such as chemical concentrations are based on experimentally derived literature ranges, and model outputs exhibit consistent and physically realistic scaling behaviour. Together, these validation steps confirm that the results represent realistic environmental estimates rather than artefacts of modelling assumptions.