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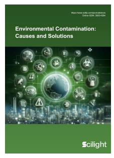

Article

Motor Vehicle Tyres as a Significant Source of Persistent Organic Pollutants Emission in Nigeria

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Abstract: Motor vehicle tyres are essential components of global rapidly expanding road transport sector, yet they constitute a major source of environmental pollution throughout their life cycle. This study presents a comprehensive assessment of Nigeria's tyre flows for 40 years (1980–2020), associated waste generation, and the content/reservoir load of three hazardous rubber additives (N-(1,3-dimethylbutyl)-N′-phenyl-p-phenylenediamine, commonly called 6PPD; chlorinated paraffins, CPs; and polycyclic aromatic hydrocarbons, PAHs). This study provides the first systematic estimation of CP, 6PPD and PAHs flows and releases associated with end-of-life tyres (ELT) in the Nigerian environment. Using Nigeria's case study on vehicle put-on-market datasets from our previous study, tyre configuration assumptions and replacement frequencies, approximately 776 million tyres (20,537 kilotons, kt) were used within the study period, while annual ELT generation amounted to 19 million units or 513 kt of ELTs. This stock of ELT (20,537 kt) contains total CPs of 267–1375 t and a substantial reservoir of 6PPD (~2000–82,000 t). The associated PAHs were estimated at 349–7332 t. The tyre particulate matter emission was estimated at 1.1–2.55 million tonnes. This study also estimated releases of these pollutants that are associated with tyre-wear particles (TWPs). For the 40 years period, the total estimated CP release ranges from ~14 t (low scenario) to ~171 t (high scenario); the 6PPD from ~110 t to ~10,216 t, while PAH releases varied from ~18 to as high as 911 t under different TWPs scenario. This has adverse human environmental health implications. This study recommends urgent implementation of a national ELT management framework.

Keywords: waste tyres; Nigeria; chlorinated paraffins; PAHs; 6PPD; microplastics; tyre wear particles; circular economy; environmental pollution

1. Introduction

Motor vehicle tyres are essential components of modern transportation systems, providing road grip, vehicle stability, load support, fuel efficiency, and passenger safety [1]. Tyres are designed as complex composite structures consisting of more than 100 individual materials, including rubber polymers, fillers, steel and textile reinforcements, vulcanization chemicals, and performance-enhancing additives [2,3]. The global tyre industry produces over two billion units each year to meet the needs of expanding vehicle populations and road transport demand [4]. As tyre consumption increases worldwide, the environmental implications of tyre materials, their use, and end-of-life handling have become major concerns across industrial and developing nations—more because the constituents of waste tyres are non-biodegradable and thermally stable [5].

In developing countries like Nigeria, the rapid increase in vehicles is largely driven by the importation of used vehicles, commonly referred to as '*tokunbo vehicles*' [6]. These vehicles frequently have partially worn tyres that are nearing or have reached the end of their service life, degrading faster than brand-new tyres. The result is an accelerated generation of waste tyres. Nigeria's vehicle fleet has seen massive growth since the 1980s, driven by a population growth, growing middle class, urbanization and heavy reliance on imports (especially used cars) due to inadequate local production and infrastructure, leading to millions entering the market and creating Africa's largest auto market. The heavy reliance on road-based mobility (and limited rail transportation) has further increased tyre consumption and turnover. This trend directly influences tyre flows and waste generation patterns. The Nigeria National Bureau of Statistics estimated vehicle population in Nigeria as at the fourth quarter of 2018 to be 11,826,033 [7]. A 2023 report by West Africa Automotive Show indicated that Nigeria accounts for 75% of 15.5 m registered vehicles in West Africa [8]. Out of 15,507,000 registered vehicles in West Africa, Nigeria accounts for 11,869,800 vehicles or 75 per cent [8]. It is estimated that over 85% of vehicle imported into Nigeria are used because they appeal to budget-conscious buyers who are seeking a balance of affordability and reliability.

Available estimates show that Nigeria has more than 11.8 million vehicles and about 400,000 vehicles are imported into the country annually [9]. At least 720,000 new vehicles are purchased annually. In 2020, NBS reported 1.3 million imported vehicles [3]. Consequently, this vast number of vehicles necessitates a corresponding number of tyres. Annually, Nigeria generates over 10 million used tyres, and this number is anticipated to rise significantly in the coming years [9].

Tyres pose significant environmental challenges across their life cycle: during production, large energy inputs and chemical additives contribute to air emissions and occupational hazards; during use, tyre wear releases particulate matter and microplastics, contributing to air, soil, and water pollution [10,11]; at end-of-life, tyres are difficult to compact, highly flammable, and resistant to biological degradation. Disposal is particularly problematic in regions with inadequate waste management systems.

In Nigeria, end-of-life tyre (ELT) management remains largely informal. Common practices include open dumping, uncontrolled burning, stockpiling, and artisanal reuse [12]. These practices contribute to multiple environmental hazards such as toxic unintentional persistent organic pollutants (POPs) release, smoke emissions, waterway obstruction, disease vector breeding, and chemical leaching [13–16]. Despite the existence of the *National Environmental (Tyre and Battery Waste Control) Regulations, 2009*, enforcement remains weak, and no national Extended Producer Responsibility (EPR) framework has been fully implemented for tyres. Although previous studies have addressed vehicle registration patterns [17] and Nigeria's transport sector challenges [18,19], there has been limited quantitative assessment of the tyre flows entering and leaving the Nigerian economy. A clear understanding of tyre consumption, replacement rates, and ELT generation is critical for designing effective policies and recycling strategies.

This study therefore aims to: (i) quantify tyre flows in Nigeria from 1980 to 2020, including tyres introduced, annual waste generation, and cumulative ELTs; (ii) identify key environmental implications of tyre use, wear, disposal, and informal recycling in Nigeria; (iii) estimate the chlorinated paraffins (CPs), (N-(1,3-dimethylbutyl)-N′-phenyl-p-phenylenediamine (commonly called 6PPD), and polycyclic aromatic hydrocarbons (PAHs) loads associated with motor vehicle tyre use in Nigeria, and (iv) recommend sustainable waste management strategies. By integrating tyre composition analysis with national flow estimates, this paper provides comprehensive evidence to guide environmental regulation, recycling investments, and sustainable tyre management in Nigeria.

2. Methods

2.1. Study Design

The study design is a simple material flow analysis (MFA) procedure similar to what had been applied in previous studies [6,20–22]. Material Flow Analysis is a systematic method used to quantify the flows and stocks of materials within a defined system—such as a city, country, industry, or production process—over a specific period of time. It tracks how materials (e.g., raw resources, intermediate products, and wastes) enter, move through, and leave the system, typically using the principle of mass balance (what goes in must either accumulate or come out). It helps to provide a clear, structured picture of resource use and waste generation. In practice, MFA is widely applied in fields like environmental management, industrial ecology, and waste management to support decision-making. By identifying inefficiencies, losses, and opportunities for recycling or reuse, MFA can guide strategies for improving resource efficiency, reducing environmental impacts, and promoting sustainable production and consumption systems.

This study employed a quantitative approach to estimate tyre flows in Nigeria over a 40-year period (1980–2020). The approach tracked tyres introduced into the market, annual tyre waste generation, and cumulative end-of-life (EoL) tyres. The analysis combined published vehicle fleet statistics [6,18,19], UNEP case-study datasets [23], tyre configuration parameters, and replacement rate assumptions consistent with industry standards. The methodological framework involved the following:

(1) data acquisition from national and international sources;
(2) vehicle fleet classification into major categories;
(3) assignment of tyre configuration parameters for each vehicle category;
(4) estimation of CPs;
(5) estimation of 6PPD;
(6) estimation of polycyclic aromatic hydrocarbons;
(7) tyre particulate matter emission, and,
(8) synthesis of results to identify trends and environmental implications.

2.2. Data Sources

2.2.1. Vehicle Put-On-Market (POM) and Fleet Data

Vehicle Put-On-Market (POM), stock, and EoL data were obtained from the United Nations Environment Programme (UNEP) Nigeria case study on vehicle flows for the period 1980–2020 [23]. Relevant information were extracted including the total vehicles introduced into the country (POM vehicles) for 1980–2020 which is estimated at 17,336,749 [23].

2.2.2. Vehicle Type Distribution

Several data sources describe the composition of Nigeria's motor-vehicle fleet, although the proportions vary depending on whether the figures are based on registration inventories, import statistics, or crash-report datasets. A widely used pollutant-inventory case study for Nigeria applied an assumed distribution of 70% cars, 29% buses, and 1% trucks [23]. More recent registration-based analyses similarly indicate that passenger cars dominate the fleet, accounting for 73.8%, compared to 24.4% buses and 1.7% trucks [23]. National Bureau of Statistics (NBS) transport reports, based on crash-recorded vehicle categories rather than full registration counts, show differing shares but still highlight the predominance of passenger vehicles [24]. Earlier national documentation, such as the *National Implementation Plan* for POPs, also emphasizes the heavy concentration of cars within Nigeria's registered vehicle stock [25]. Collectively, these references support the observation that passenger cars constitute roughly 70–74% of Nigeria's fleet, while the relative shares of buses and trucks vary across datasets. These are also close to the Nigerian fleet patterns reported in FRSC and national transport studies [18].

Therefore, for fair national fleet composition statements, the following distribution was applied in this study: cars: 70%; buses: 29%; trucks: 1%. These proportions reflect the dominance of passenger vehicles and light commercial buses in Nigeria's transport system.

2.3. Tyre Configuration and Replacement Assumptions

Tyre configuration and replacement practices significantly impact vehicle safety and environmental sustainability. Many vehicles, especially imported used ones, often have mismatched worn tyres, and drivers sometimes prioritize cost over quality, neglecting regular maintenance like rotations and pressure checks. Though international standards suggest replacing tyres every 6–10 years, but due to harsher driving conditions in Nigeria (e.g., poor roads, heat) local sources suggest 2–3 years [26–28].

The assumptions for tyre configuration according to vehicle type are:

- Cars: 5 tyres/vehicle (usually 1 spare); replace 1 set every 3 years
- Buses: 7 tyres/vehicle (dual rear wheels, 1 spare common); replace 1 set every 2 years
- Trucks: 12 tyres/vehicle (heavy-duty, typically 10 + 2 spares); replace 1 set every 2 years

The assumptions for replacement frequencies were based on average tyre lifespans under Nigerian road conditions (rough roads, variable weather, and prevalence of used tyres). These assumptions are consistent with tyre manufacturers' guidance and regional transport maintenance patterns.

2.4. Computational Procedures

The formulas applied to estimate tyre and CP flows in this study are given below:

Tyres Introduced into Nigeria (1980–2020)

$$Tyres\ Introduced = \sum(POM \times Tyres\ per\ Vehicle) \quad (1)$$

Mass of CPs

$$Mass\ of\ CPs = \sum(number\ of\ tyres \times tyre\ mass \times CP\ concentration) \quad (2)$$

All computations were performed separately for cars, buses, and trucks before aggregating to national totals.

2.5. Environmental and Material Composition Review

A comprehensive literature review was conducted using scientific databases (ScienceDirect, PubMed, SpringerLink, JSTOR, and Taylor & Francis). The review focused on: tyre chemical and material composition; microplastic generation; tyre wear particles (TWPs); chemical leaching of 6PPD, PAHs; air emissions from manufacturing and burning; environmental impacts of tyre disposal and recycling. Key sources included international reviews [10,29], toxicological assessments [30], and environmental emission studies [15,16,31].

3. Results and Discussion

3.1. Total Tyres Introduced into Nigeria (1980–2020)

Based on vehicle POM data (Figure 1) and tyre configuration assumptions, an estimated 97,952,632 tyres were introduced into the Nigerian economy between 1980 and 2020 (Table 1). A summary of the estimated number of tyres introduced into Nigeria (1980–2020) is presented in Figure 2. The ratio of vehicles use is 70:29:1 for cars, buses and trucks while the corresponding number is 5 tyres per car; 7 for buses and 12 per truck (including the spare tyre).

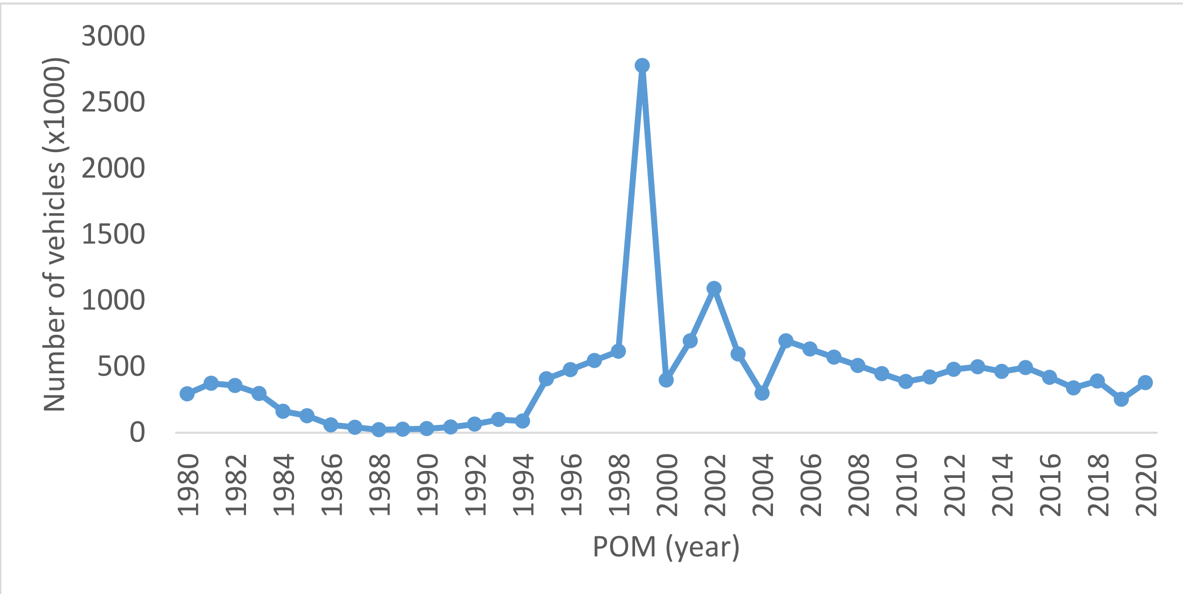

Figure 1. Motor Vehicles POM for 40 years in Nigeria (1980–2020).

Figure 1 shows sharp increases in POM during 1999–2002 and displays long-term growth trend with cyclical fluctuations reflecting economic and policy shifts. The sharp spike in vehicle imports between 1999 and 2002 contributed significantly to tyre introduction due to relaxed import duties and a nationwide vehicle registration campaign. Figure 1 obviously shows that growth in tyre introduction closely mirrors fluctuations in economic activity and vehicle import policies.

The expansion of the Nigerian vehicle fleet over the last four decades is the fundamental driver of tyre consumption. With over 17.3 million vehicles introduced into the market between 1980 and 2020, this study estimates that approximately 98 million tyres entered the Nigerian economy during this period. This aligns with known patterns of rising private car ownership, commercial transport needs, and a heavy reliance on road transport for goods and services in Nigeria.

The surge in vehicle POM during the late 1990s to early 2000s, linked to import deregulation and mass registration campaigns, resulted in a corresponding increase in tyre introduction. Because tyres have a relatively short lifespan, especially under poor road network and climatic conditions akin to Nigeria, this translated into higher rates of annual waste tyre generation.

Table 1. Number of motor vehicles (and corresponding number of tyres) POM for 40 years (1980–2020). Data source: Green Growth Knowledge Partnership [23].

POM (Year)	Number of POM Vehicles	Number of Vehicles			Number of Tyres		
		Cars	Buses	Trucks	Cars	Buses	Trucks
1980	293,191	205,233	85,025	2932	1,026,169	595,177	35,183
1981	372,907	261,034	108,143	3729	1,305,175	757,001	44,749
1982	356,586	249,610	103,409	3565	1,248,051	723,869	42,790
1983	294,942	206,459	85,533	2949	1,032,297	598,732	35,393
1984	161,003	112,702	46,691	1610	563,510	326,836	19,320
1985	127,446	89,212	36,959	1274	446,061	258,715	15,293
1986	58,138	40,696	16,860	581	203,483	118,020	6976
1987	39,851	27,895	11,557	398	139,478	80,897	4782
1988	20,899	14,629	6060	209	73,146	42,425	2508
1989	25,543	17,880	7407	255	89,400	51,852	3065
1990	29,438	20,606	8537	294	103,033	59,759	3532
1991	41,842	29,289	12,134	418	146,447	84,939	5021
1992	63,896	44,727	18,529	638	223,636	129,709	7667
1993	98,887	69,220	28,677	988	346,104	200,740	11,866
1994	87,233	61,063	25,297	872	305,315	177,083	10,468
1995	406,839	284,787	117,983	4068	1,423,937	825,883	48,820
1996	476,300	333,410	138,127	4763	1,667,050	966,889	57,156
1997	545,765	382,035	158,272	5457	1,910,178	1,107,903	65,492
1998	615,222	430,655	178,414	6152	2,153,277	1,248,900	73,826
1999	2,778,440	1,944,908	805,747	27,784	9,724,540	5,640,233	333,413
2000	396,920	277,844	115,106	3969	1,389,220	805,747	47,630
2001	694,610	486,227	201,437	6946	2,431,135	1,410,058	833,53
2002	1,091,530	764,071	316,543	10,915	3,820,355	2,215,806	130,983
2003	595,380	416,766	172,660	5953	2,083,830	1,208,621	71,445
2004	297,690	208,383	86,330	2976	1,041,915	604,310	35,723
2005	694,610	486,227	201,437	6946	2,431,135	1,410,058	83,353
2006	632,421	442,694	183,402	6324	2,213,474	1,283,814	75,890
2007	570,244	399,170	165,370	5702	1,995,854	1,157,595	68,429
2008	508,067	355,646	147,339	5080	1,778,235	1,031,376	60,968
2009	445,886	312,120	129,307	4458	1,560,601	905,148	53,506
2010	386,244	270,370	112,011	3862	1,351,854	784,075	46,349
2011	419,993	293,995	121,798	4199	1,469,976	852,586	50,399
2012	478,319	334,823	138,712	4783	1,674,117	970,987	57,398
2013	498,627	349,038	144,601	4986	1,745,195	1,012,213	59,835
2014	462,806	323,964	134,213	4628	1,619,821	939,496	55,536
2015	492,008	344,405	142,682	4920	1,722,028	998,776	59,041
2016	418,561	292,992	121,382	4185	1,464,964	849,679	50,227
2017	338,384	236,868	98,131	3384	1,184,344	686,919	40,606
2018	390,443	273,310	113,228	3904	1,366,551	792,599	46,853
2019	251,465	176,025	72,925	2514	880,127	510,474	30,176
2020	378,173	264,721	109,670	3782	1,323,606	767,691	45,381
Total	17,336,749	12,135,709	5,027,645	173,352	60,678,624	35,193,590	2,080,401

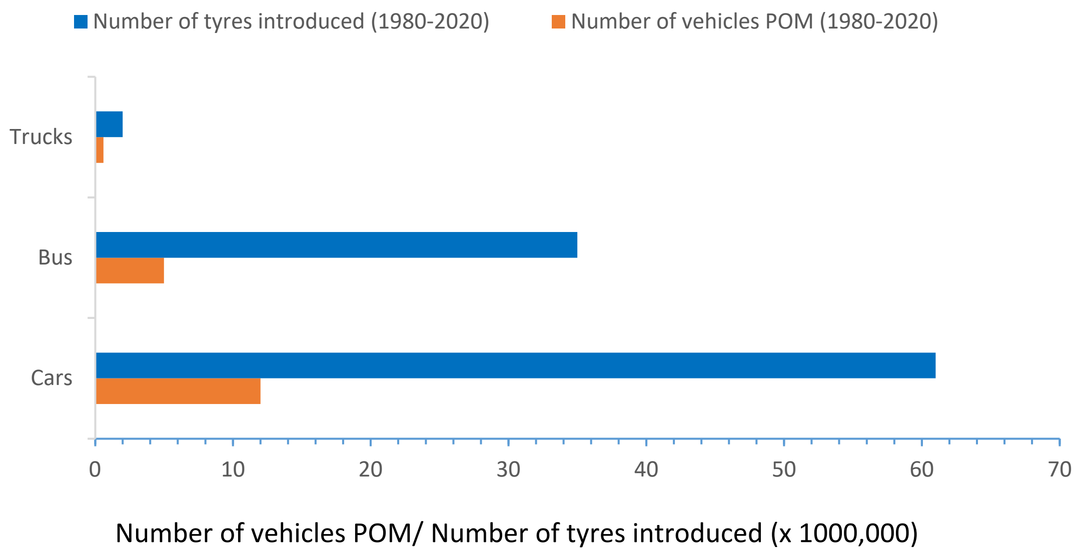

Figure 2. Number of vehicles POM in Nigeria and the estimated associated tyres (1980–2020).

3.2. Waste Tyre Generation (1980–2020)

Applying replacement frequencies, the estimated amount of tyres used or that reached end-of-life in the period, 1980–2020, according to vehicle type is presented in Table 2. This was estimated using Equations (3) and (4):

Total number of tyres (*T*) used by any category of vehicles within the period (*P*) of 40 years is given by:

$$T = n + (n \times N) \quad (3)$$

Where n is the number of tyres of a vehicle category POM in a particular year (Table 1).

$$N = \frac{P - y}{f} \quad (4)$$

N = number of replacements within a period (P) (i.e., 40 years); *y* = the year a particular vehicle category was POM; e.g., for vehicles POM in 1980, *y* = 0; for 1981, *y* = 1; while *f*, the replacement frequencies, is every 3 years for cars; and every 2 years for bus and trucks.

For example, for cars POM in 1980, *N* = (40−0)/3 = 13; and for cars POM in 1988, $N = (40 - 8)/3 \approx 10.7$.

The calculation estimates (Table 2) that Nigeria generated approximately 776 million waste tyres for motor vehicles POM in 1980–2020. This gives approximately 19 million annual waste tyre generation. This result is comparable with national reports from a national survey reporting 20 million annual tyre imports (giving an average of 800 million over 40 years) [32]. There was an additional local production of motor vehicle tyres put at 5.7 million annually [33], giving about 200 million in 40 years. Buses and trucks, though fewer in number, generate disproportionately high waste due to faster tyre wear under high load-bearing conditions and poor road network.

Nigeria's transport sector is characterized by extensive importation of used vehicles, many of which arrive with partially worn tyres. These tyres reach end-of-life quickly due to prior use overseas, exposure to degraded roads, higher ambient temperatures (compared to country of origin/manufacture of the tyres), overloading of vehicles, and poor maintenance culture. Considering that the majority of Nigerian motorists rely on imported used tyres as replacements, this further shortens replacement cycles.

These dynamics accelerates the annual generation of ELTs, contributing to the estimated 776 million waste tyres as of 2020. This figure is disproportionately high relative to Nigeria's population and GDP, illustrating the environmental burden imposed by dependence on the importation and consumption of used-vehicles and used tyres.

A significant portion resides in dumpsites, water channels, or informal stockpiles due to absence of formal ELT management systems.

Table 2. Number of tyres used by each vehicle category (POM within 40 years; 1980–2020).

POM (Year)	Number of Replacements of Vehicle Tyre Sets (1980–2020)			Total Tyres Used (1980–2020)			Total Motor Vehicle Tyres (1980–2020)
	Cars	Buses	Trucks	Cars	Buses	Trucks	
1980	13	20	20	14,366,359	12,498,732	738,841	27,603,932
1981	13	20	20	18,272,443	15,897,025	939,725	35,109,194
1982	13	19	19	17,472,714	14,477,391	855,806	32,805,912
1983	12	19	19	13,419,861	11,974,645	707,861	26,102,367
1984	12	18	18	7,325,636	6,209,885	367,087	13,902,609
1985	12	18	18	5,798,793	4,915,592	290,577	11,004,962
1986	11	17	17	2,441,796	2,124,362	125,578	4,691,736
1987	11	17	17	1,673,742	1,456,155	86,078	3,215,975
1988	11	16	16	877,758	721,224	42,634	1,641,616
1989	10	16	16	983,405.5	881,489	52,108	1,917,002
1990	10	15	15	1,133,363	956,146	56,521	2,146,030
1991	10	15	15	1,610,917	1,359,028	80,336	3,050,281
1992	9	14	14	2,236,360	1,945,633	115,013	4,297,006
1993	9	14	14	3,461,045	3,011,109	177,996	6,650,150
1994	9	13	13	3,053,155	2,479,161	146,551	5,678,868
1995	8	13	13	12,815,429	11,562,364	683,489	25,061,282
1996	8	12	12	15,003,450	12,569,557	743,028	28,316,035
1997	8	12	12	17,191,598	14,402,738	851,393	32,445,729
1998	7	11	11	17,226,216	14,986,808	885,919	33,098,943
1999	7	11	11	77,796,320	67,682,798	4,000,953	149,480,072
2000	7	10	10	11,113,760	8,863,223	523,934	20,500,918
2001	6	10	10	17,017,945	15,510,641	916,885	33,445,471
2002	6	9	9	26,742,485	22,158,059	1,309,836	50,210,380
2003	6	9	9	14,586,810	12,086,214	714,456	27,387,480
2004	5	8	8	6,251,490	5,438,796	321,505	12,011,791
2005	5	8	8	14,586,810	12,690,525	750,179	28,027,513
2006	5	7	7	13,280,841	10,270,517	607,124	24,158,482
2007	4	7	7	9,979,270	9,260,762	547,434	19,787,467
2008	4	6	6	8,891,172	7,219,632	426,776	16,537,581
2009	4	6	6	7,803,005	6,336,040	374,544	14,513,589
2010	3	5	5	5,407,416	4,704,452	278,095	10,389,963
2011	3	5	5	5,879,902	5,115,514	302,395	11,297,812
2012	3	4	4	6,696,466	4,854,938	286,991	11,838,395
2013	2	4	4	5,235,583	5,061,064	299,176	10,595,824
2014	2	3	3	4,859,463	3,757,984	222,147	8,839,594
2015	2	3	3	5,166,084	3,995,105	236,164	9,397,353
2016	1	2	2	2,929,927	2,549,036	150,682	5,629,645
2017	1	2	2	2,368,688	2,060,758	121,818	4,551,265
2018	1	1	1	2,733,101	1,585,198	93,706	4,412,006
2019	0	1	1	880,127	1,020,948	60,351	1,961,427
2020	0	0	0	1,323,605	767,691	45,381	2,136,677
				407,894,310.5	347,418,939	20,537,073	775,850,334
SUM				407,894,311	347,418,939	20,537,073	775,850,334

3.3. POPs in Motor Vehicle Tyres—Estimation of Flows and Releases

Recent studies have shown that tire and road-wear particles (TRWPs) serve as carriers for CPs, PAHs and 6PPD-quinone [34,35]. These mixtures pose cumulative ecological risks, particularly in urban watersheds.

3.3.1. Chlorinated Paraffin

Chlorinated paraffins (CPs), including short-chain (SCCPs), medium-chain (MCCPs), and long-chain chlorinated paraffins (LCCPs), are widely used as plasticizers, flame retardants, and flexibility enhancers in rubber formulations [36,37]. SCCPs/MCCPs are not added as plasticisers in tyres but have been detected at levels below 100 mg/kg indicating contamination e.g., from use of CP oils as lubricants in production [38]. SCCPs and MCCPs have been listed as POPs in the Stockholm Convention [36,38] and therefore their presence in tyres are of concern [39].

Presented in Table 3 is a summary of pollutant groups identified in ELTs their concentration ranges from literature. Using this information (Table 3), the amounts of CPs in the ELTs in Nigeria were estimated (using equation 2) using an ELT CP concentration range of 13 mg/kg to 67 mg/kg. The wide range reflects variability in CP concentrations in tyres, as measured by Brandsma et al. [40], who found ΣCP levels ranging from 13–67 mg/kg in car tyre rubber and related recyclates and tile products.

These values were used to make both low estimate and high estimate for the levels/releases of CPs in Nigeria using the varying tyre masses—for cars, buses and trucks. The tyre mass assumptions used for POPs mass calculations are presented below:

- Car: 9 kg/tyre (UNEP/ETRMA tyre mass ranges)
- Bus: 45 kg/tyre (heavy-duty commercial tyres)
- Truck: 60 kg/tyre (heavy-duty truck tyres)
- Weighted average (Nigeria fleet): 23.8 kg/tyre (based on stock proportions)

Table 3. Concentrations of POPs in tyres.

Pollutant (Group)	Typical Reported Concentration Ranges in Tyres	Notes from Representative Studies	References
PAHs (total, tyre extender oils)	• ~17–357 mg/kg total PAHs; • ~1–16 mg/kg (mean ≈ 5 mg/kg) of BaP (benzo[a]pyrene)	Note: above data are from EU risk/opinion and long-term PAH studies on ELT recyclates; PAH profile depends on extender oils and analysis method	[41,42]
Chlorinated paraffins (∑CPs, C10–C30: SCCP/MCCP/LCCP mixtures)	≈13–67 µg/g (=13–67 mg/kg) ∑CP(C10–C30)	The study measured ΣCP(C10–C30) in tyres, tyre recyclates and related tile products (MCCPs often dominant).	[40]
6PPD	• Low: 100 mg/kg; • Mid: 571 mg/kg; • High: 4000 mg/kg	The mid scenario (571 mg/kg) is taken from the Interstate Technology & Regulatory Council (ITRC) reconnaissance / guidance which reports an average value of ~571 mg/kg across samples	[43]

A quantitative estimate of CPs present in motor vehicle tyres in Nigeria (1980–2020) are presented in Table 4. These results provide the first systematic estimation of CPs releases associated with tyres in the Nigerian environment–considering both a low estimate (13 mg/kg) and a high estimate (67 mg/kg) of CPs in tyres.

Table 4 shows that between 267 t (low estimate) and 1375 t (high estimate) of CPs entered Nigeria through approximately 776 million tyres used in the Nigerian transportation system between 1980 and 2020. The distribution of CPs among vehicle categories reveals that trucks and buses contribute disproportionately to the total CP mass, despite representing only 47% of tyre count. This is due to their higher tyre masses (45–60 kg per tyre), consistent with international tyre mass characterizations [44].

It needs to be stressed that the total estimated amount of SCCPs/MCCPs imported to Nigeria in rubber between 1996 to 2020 was 33,700 t [45] and therefore tyres only contribute to between 0.1% and maximum 5% of SCCP/MCCP imports to Nigeria.

Table 4. Estimated mass of CPs in tyres used in Nigeria (1980–2020).

Vehicle Type	Number of Used Tyres	Tyre Mass in Kiloton (kt)	Estimation of CP Amounts (t)	
			Low Estimate in Ton (t)	High Estimate in Ton (t)
Cars	407,894,312	3671	47.7	246
Buses	347,418,950	15,634	203	1047
Trucks	20,537,081	1232	16	82
Total	775,850,343	20,537	267	1375

Note: Estimates of CP quantities are based on both a low estimate (13 mg/kg) and a high estimate (67 mg/kg) of CPs in tyres.

The historical inflow of CPs in tyres indicates that Nigeria has accumulated a substantial legacy stock of CPs that now reside within in-use tyres, waste flows, informal recycling channels, and disposed tyres in dumpsites. Given that SCCPs are listed as Stockholm Convention POPs and MCCPs are under global evaluation for toxicity and persistence [36,38,39], the magnitude of these inflows presents regulatory and environmental significance.

Studies indicate that TWPs act as vectors for additives including the CPs and the other two highlighted additives in Table 4, enabling their accumulation in soils, road dust, stormwater, and aquatic ecosystems [10,46]. This dynamic is particularly relevant to Nigeria due to heavy traffic density in urban areas and poor road infrastructure, which likely amplifies mechanical abrasion compared to high income countries. This study estimated releases of CPs, 6PPD and PAHs that are associated with TWPs. The leaching of additives into water and soil under warm, humid conditions prevalent in West Africa are likely higher compared to colder climates [15,16]. In addition, informal burning of tyres—common in abattoirs, metal workshops, and waste dumps—can additionally generate toxic chlorinated unintentional POPs and other organic combustion by-products [31], contributing to hazardous atmospheric exposure.

Nigeria has accumulated a large legacy stock of CPs in tyres, and this reservoir continues to grow with ongoing imports. Annual release rates are high, meaning CPs are entering the environment faster than they are being managed. Informal waste tyre practices (burning, dumping) accelerate environmental exposure and potential human health risks. The magnitude of CP flows suggests a clear need for regulatory action, especially given that SCCPs are internationally regulated and MCCPs increasingly recognized as environmental hazards. The total CP loads reported for Nigeria are consistent with international research demonstrating that tyres are a significant global source of CP emissions [40,46].

It needs to be stressed that the total estimated amount of SCCPs/MCCPs imported to Nigeria in rubber between 1996 to 2020 was 33,700 t [45].

CPs are listed or under review under international treaties due to toxicity, endocrine-disrupting properties, carcinogenic potential, and persistence [39]. Their continual cycle through the Nigerian environment, from tyre wear to burning to leaching, calls for early national monitoring and risk assessment.

3.3.2. Estimation of Flow of 6PPD and 6PPD-Quinone (6PPD-Q)

N-(1,3-dimethylbutyl)-N′-phenyl-p-phenylenediamine (6PPD) is an antiozonant/antioxidant added to tire rubber for decades to protect tires from ozone cracking and to prolong service life. As tires abrade during driving, tire and road wear particles (TRWPs) containing 6PPD are released to roadsides and urban surfaces, where they become susceptible to atmospheric and aqueous transformation [47]. The mass of the antioxidant 6PPD in tyres was estimated using tyre counts and mass distributions from previous sections. The estimation covered tyres used from 1980–2020, following this equation:

$$Total\ 6PPD\ mass\ (kg = total\ tyre\ mass\ (kg) \times \frac{6PPD\ concentration\ (mg\ 6PPD\ per\ kg\ tyre)}{1{,}000{,}000} \quad (5)$$

Note: the total tyre mass for each stage was calculated from the total tyre used for each category multiplied by representative tyre mass per unit. Three concentration scenarios were considered to bracket uncertainty (Table 5):

- Low: 100 mg/kg (conservative)
- Mid-range: 571 mg/kg (average in ITRC tyre/rubber samples [43]
- High: 4000 mg/kg (≈0.4% by mass, upper-bound in tyre chemistry literature [48].

These scenarios therefore present a plausible range of 6PPD *stocks* contained within tyres and not direct measures of environmental fluxes or concentrations in runoff, which depend on wear rates, weathering and chemical transformation (e.g., formation of 6PPD-quinone).

Table 5. Estimated 6PPD contained in tyres used in Nigeria for 40 years.

Vehicle Category	Number of Tyres Used	Total Tyre Mass (kt)	Estimate 6PPD Quantities (t)		
			Low	Mid	High
Cars	407,894,312	3671	367	2096	14,684
Buses	347,418,950	15,634	1563	8927	62,536
Trucks	20,537,081	1232	123	703	4928
Total	775,850,343	20,537	2053	11,726	82,148

Note: Estimates of 6PPD quantities are based low (100 mg/kg); mid (571 mg/kg), and high (4000 mg/kg) concentrations of 6PPD in tyres.

The mid scenario (571 mg/kg) is taken from the Interstate Technology & Regulatory Council (ITRC) reconnaissance/guidance which reports an average value of ~571 mg/kg across samples—a defensible midpoint for stock estimates [43]. The high scenario (0.4% ≈ 4000 mg/kg) reflects reported formulation ranges for 6PPD in tyre rubber (commonly cited 0.4–2% by mass in industry/technical reviews) [48].

6PPD transforms to 6PPD-quinone (6PPD-Q) by reaction with ozone/oxidants and 6PPD-Q has been linked to acute aquatic toxicity (coho salmon studies; [34]). Use of 6PPD stocks as an indicator therefore implies potential for environmentally relevant transformation and risk; monitoring should include 6PPD-Q [34]. The estimated 6PPD contained in tyres considering three scenarios are presented in Table 5.

Under conservative to mid-range assumptions, Nigeria's tyre waste stream represent several thousand tonnes of 6PPD (~2000 t to ~82,000 t of 6PPD)—a substantial reservoir that could generate environmentally relevant loads of 6PPD and its toxic transformation product 6PPD-Q via wear, leachate, and open burning pathways.

Laboratory and field work have shown that 6PPD is readily transformed (particularly by gas-phase ozone and during photochemical/ozonation processes) into a suite of transformation products; the best-studied and most environmentally concerning product is 6PPD-quinone (6PPD-Q). 6PPD-Q has been detected in roadway runoff, stormwater, and urban surface waters and in leachates of tire wear particles at concentrations that can be locally high during runoff events. Quantitative surveys across multiple regions report episodic 6PPD-Q concentrations in roadway runoff and urban streams often in the low $ng \cdot L^{-1}$ to several hundred $ng \cdot L^{-1}$ (and, in some samples, $>\mu g \cdot L^{-1}$ during pulses) [49].

A landmark study linked 6PPD-Q to acute, rapid mortality of migrating coho salmon exposed to stormwater from urban streams; coho salmon mortality occurs at extremely low (nanogram-per-litre) concentrations in laboratory exposures. Subsequent ecotoxicological studies have confirmed high sensitivity in several salmonid species and demonstrated adverse effects in other aquatic organisms. These findings have driven regulatory and scientific attention because the concentrations measured episodically in stormwater can exceed lethal thresholds for sensitive fish species [34].

Current evidence indicates stormwater runoff is the principal pathway by which 6PPD-Q reaches aquatic systems; however, detections in roadside soils and in extracts of TRWPs indicate potential for broader terrestrial exposure and possible bioavailability via multiple routes. Important knowledge gaps remain and these include:

(1) long-term chronic toxicity across taxa,
(2) human exposure pathways and health effects,
(3) environmental persistence and degradation in soils/sediments,
(4) mixture effects with other TRWP contaminants, and,
(5) scalable remediation or management measures (e.g., stormwater treatment efficacy, tire formulation alternatives).

Several recent guidance and review documents summarize current monitoring results and propose research and regulatory priorities [49,50].

3.3.3. Polycyclic aromatic hydrocarbons

From the EU risk/opinion and long-term PAH studies on ELT recyclates, the reported concentration of PAHs is ~17–357 mg/kg total PAHs for tyre tread; BaP (benzo[a]pyrene) ~1–16 mg/kg (mean ≈ 5 mg/kg) (values from surveys of tyre treads and rubber recyclates) [41]. PAH profile depends on extender oils and analysis method.

Therefore, in this study, a low estimate using the concentration of 17 mg/kg and a high estimate using 357 mg/kg were made using the following equation:

$$PAH = m \times c \quad (6)$$

where *PAH* is the amount of PAHs present in Nigerian environment (1980–2020) through motor vehicle tyres (for car, bus or trucks); *m* is the mass of tyre (1980–2020), and *c* is the concentration of PAHs in tyre.

Table 6. Estimated PAHs contained in tyres.

Vehicle Category	Total Tyre Mass (kt)	Low Estimat e * (t)	High ** (t)
Cars	3671	62.4	1311
Buses	15,634	266	5581
Trucks	1232	20.9	440
Total	20,537	349	7332

Note: * using a low PAH concentration of 17 mg/kg; and a ** high concentration of 357 mg/kg.

Table 6 presents the mass of PAHs contained in tyres based on low (17 mg/kg) and high (357 mg/kg) concentration scenarios, consistent with ranges reported in the scientific literature [51,52].

Considering the total tyre mass in Nigeria (cars, buses, and trucks combined) of 20,537 kt, the estimated PAHs in all tyres is 349 t (for low PAHs content scenario) and 7332 t (for high scenario). This indicates that even under conservative assumptions, nearly half a million kilograms of PAHs were present in vehicle tyres used in Nigeria over the studied period. Under high-concentration conditions, the estimated PAH content 7332 t, implying a potentially large reservoir of PAH-laden material in the Nigerian roadways and dump sites.

Buses contribute the highest PAH loads, reflecting their greater tyre mass and high-resilience rubber compounds enriched with PAH-containing extender oils. Studies confirm that heavier commercial tyres tend to contain higher PAH concentrations [52,53]. PAHs from tyre wear are of particular concern because:

- PAHs are carcinogenic, mutagenic, and persistent, with several compounds (e.g., benzo[a]pyrene) classified under Group 1 or 2A carcinogens [54];
- they accumulate in roadside soils, atmospheric particulates, stormwater runoff and urban waterways; and,
- in Nigeria, where rainfall frequently mobilizes roadside contaminants into drainage channels, PAHs from tyres may significantly contribute to the contamination of wetlands, agricultural soils, and river systems.

These findings are consistent with international research showing that tyre-derived PAHs are a major component of microplastic-associated organic pollutants in the environment [55,56].

3.3.4. Tyre Particulate Matter (TPM) Released over the Lifetime of Tyres

Tyre particulate matter (TPM) released over the lifetime of tyres was estimated by multiplying the number of tyres in each category by mass loss (Table 7; [57]) per tyre over its service life (kg/tyre).

$$TPM\ (kg) = tyre\ count \times mass\text{-}loss\ per\ tyre\ (kg) \quad (7)$$

Reported in this section is TPM released over the lifetime of tyres considering three scenarios to bracket uncertainty: *low*, *mid*, and *high*, defined by different per-tyre lifetime wear masses for passenger-car, bus and truck tyres (see Table of assumptions; Table 7). This estimate quantifies bulk mass of tyre material abraded and released during the tyre service life (includes particles of all sizes) and is not a direct measurement of specific PM fractions (e.g., $PM_{2.5}$) or of the fraction that enters water versus remains on roadsides.

Table 7. Assumptions of mass loss per tyre in its lifetime (kg).

Vehicle Category	Low Scenario Mass Loss per Tyre	Mid Scenario Mass Loss per Tyre	High Scenario Mass Loss per Tyre
Cars	0.9	1.1	1.5
Buses	1.8	3.0	5.0
Trucks	5.0	7.5	10.0

Assumption scenarios are from: Kudin et al. [57]; Grigoratos et al. [58]; EMEP/EEA [59].

Reviews and measurement studies report passenger-car tyre mass losses on the order of ~1.0–1.5 kg per tyre lifetime and vehicle-level wear factors often expressed as ~50–150 mg/vehicle·km (giving similar lifetime totals depending on mileage). Heavy-duty tyres lose substantially more mass per tyre over their service life (see Grigoratos et al. [58]) for reviews and the EEA/EMEP guidebook [59] for recommended emission-factor ranges). The estimated mass of total particulate matter loss from tyre (1980–2020) is presented in Table 8.

Table 8. Mass of total particulate matter loss from tyre (1980–2020).

Vehicle Category	Total Number of Tyre Used	Low Scenario Mass Loss (t)	Mid Scenario Mass Loss (t)	High Scenario Mass Loss (t)
Cars	407,894,312	367,105	448,684	611,841
Buses	347,418,950	625,354	1,042,257	1,737,095
Trucks	20,537,081	102,685	154,028	205,371
Total	775,850,343	1,095,144	1,644,969	2,554,307

The passenger-car lifetime loss values used are consistent with multiple reviews that report ~1–1.5 kg tyre mass loss per tyre lifetime and vehicle-level wear factors that typically range from ~50–150 mg/vehicle·km (depending on tyre, driving, road surface) [58]. The total values presented above (e.g., tens to a few hundred kilotons) are of the same *order of magnitude* expected for national tyre-wear reservoirs in countries with large fleets. For context, global tyre wear is estimated at several million tonnes per year; national totals scale by fleet size and per-vehicle mileage [60].

Table 8 presents estimates of TWPs emitted by vehicles in Nigeria over a forty-year period. The results show that cars used the highest number of tyres (407.9 million), but their total particulate matter loss is lower than that of buses. Buses, though fewer in number than cars, contributed a significantly larger mass of TWPs. Trucks contributed the lowest TWP mass. The trend clearly demonstrates that heavier vehicles emit substantially more tyre-wear particles per tyre than lighter passenger cars. This aligns with international findings that TWPs increases with vehicle mass, load, and braking frequency [29,61].

The combined total TWPs emitted by all vehicle categories over the period is extremely high: 1.1 million tonnes for low scenario and 2.55 million tonnes for high emission scenario. These values indicate that tyre abrasion is a major non-exhaust particulate emission source in Nigeria, consistent with global evidence that tyre wear can surpass exhaust emissions as vehicles with better emission controls increase [4,62].

The implications for Nigeria include significant release of microplastics into terrestrial and aquatic environments; elevated human exposure to hazardous compounds such as zinc, PAHs, and 6PPD-quinone found in tyre particles [56]; potential accumulation of tyre-derived pollutants in urban dust, roadside soils, and drainage systems, especially in heavily trafficked cities like Lagos, Abuja, and Port Harcourt.

3.4. Estimation of Pollutants Released to the Environment through TWPs

TWPs released into the environment contains POPs and the amounts of CPs, 6PPD and PAHs released into the environment through TWPs were also estimated in this study as described below using the total particulate matter loss from tyre as presented in Table 8 for low (total release of 1,095,144 t), mid (total release of 1,644,969 t) and high (total release of 2,554,307 t) scenarios.

3.4.1. CPs Already Released through TWPs

The amounts of CPs already released into the environment (over the 40 years period) through TWPs in Nigeria were estimated using an ELT CP concentration range of 13 mg/kg (low scenario) to 67 mg/kg (high scenario) following the equation given below (see Table 9):

$$\textit{Mass of CP} = \sum(\textit{tyre mass loss} \times \textit{CP concentration}) \quad (8)$$

Table 9. Amount of CPs already released (t) into the environment through TWPs (1980–2020).

Vehicle Category	Low TWPs Release Scenario		Mid TWPs Release Scenario		High TWPs Release Scenario	
	Low CP Release Scenario	High CP Release Scenario	Low CP Release Scenario	High CP Release Scenario	Low CP Release Scenario	High CP Release Scenario
Cars	4.8	25	5.8	30	8	41
Buses	8.1	41.9	13.5	69.8	22.6	116
Trucks	1.3	6.9	2	10.3	2.7	13.8
Total	14.2	73.8	21.3	110	33.3	171

Table 9 quantifies the cumulative release of CPs into the Nigerian environment through TWPs between 1980 and 2020 under low, mid, and high TWP scenarios. Across all scenarios, trucks consistently dominate CP emissions, contributing the largest share of tyre mass loss and, consequently, CP release. Under the high scenario, buses account for approximately 116 t of CPs, compared with 41 t for cars and 13.8 t for trucks, reflecting the heavier axle loads, higher tyre wear rates, and longer travel distances typically associated with freight vehicles [10,63].

The total estimated CP release is estimated from ~14 t (low scenario) to ~171 t (high scenario) over the 40-year period, highlighting the relevance of CP emissions to assumptions about TWPs generation and CP content in tyres. These findings are environmentally significant because CPs are POPs known for their environmental persistence, bioaccumulation potential, and toxicity, particularly in aquatic and sedimentary environments [40]. The results suggest that road traffic (especially heavy-duty vehicles) represents a historically important but often under-recognized source of CP contamination [64] in Nigeria, complementing more commonly cited sources such as industrial products and waste streams. It needs to be stressed that the total estimated amount of SCCPs/MCCPs imported to Nigeria in rubber between 1996 to 2020 was 33,700 t [45].

3.4.2. 6PPD Already Released through TWPs

Estimates of 6PPD quantities are based on low (100 mg/kg); mid (571 mg/kg), and high (4000 mg/kg) concentrations of 6PPD in tyres and calculated using the total particulate matter loss from tyre as presented in Table

8 for low (total release of 1,095,144 t), mid (total release of 1,644,969 t) and high (total release of 2,554,307 t) scenarios:

$$Mass\ of\ 6PPD = \sum(tyre\ mass\ loss \times 6PPD\ concentration) \quad (9)$$

Presented in Table 10 are the estimated 6PPD releases, a widely used anti-degradant in tyres, under low, mid, and high concentration assumptions for each TWPs scenario. The data indicate substantially higher mass releases of 6PPD compared with CPs, reaching ~110 t (low scenario) and up to ~10,216 t (high scenario).

Table 10. Amount of 6PPD (t) already released into the environment through TWPs (1980–2020).

Vehicle Category	Low TWPs Release Scenario			Mid TWPs Release Scenario			High TWPs Release Scenario		
	Low 6PPD Release Scenario	Mid 6PPD Release Scenario	High 6PPD Release Scenario	Low 6PPD Release Scenario	Mid 6PPD Release Scenario	High 6PPD Release Scenario	Low 6PPD Release Scenario	Mid 6PPD Release Scenario	High 6PPD Release Scenario
Cars	37	210	1468	45	256	1795	62	349	2447
Buses	63	357	2501	104	595	4169	174	992	6948
Trucks	10	59	411	15	88	616	21	117	821
Total	110	626	4380	164	939	6580	257	1458	10,216

As observed for CPs, trucks are the largest contributors, accounting for more than half of the total 6PPD emissions in each scenario, followed by buses and then cars. This pattern reflects both higher tyre mass loss and the widespread use of 6PPD in heavy-duty tyres to prevent oxidative degradation [10,64]. The magnitude of these emissions is particularly noteworthy given growing evidence that 6PPD and its transformation product, 6PPD-quinone (6PPD-q), are acutely toxic to aquatic organisms, even at low concentrations [65].

From a Nigerian context, the long-term accumulation implied by these figures raises concerns about chronic inputs of 6PPD-derived compounds into urban runoff, roadside soils, and surface waters. The results reinforce recent international findings that TWPs is a major, continuous source of 6PPD to the environment and underscore the need for targeted monitoring and mitigation strategies, especially in regions with rapidly expanding vehicle fleets and limited stormwater treatment [64].

3.4.3. PAHs Already Released through TWPs

The data for TWPs releases for 40 years (1980–2020) as presented in Table 8 for low (total release of 1,095,144 t), mid (total release of 1,644,969 t) and high (total release of 2,554,307 t) scenarios were used to estimate both low and high PAHs releases (using PAHs concentration of 17 mg/kg and a high concentration of 357 mg/kg (see Table 3) [41,42] using the following equation:

$$Mass\ of\ PAHs = \sum(tyre\ mass\ loss \times PAHs\ concentration) \quad (10)$$

Table 11 summarizes the estimated releases of PAHs associated with TWPs over the same period. Total PAH emissions increase from ~18–391 t (low–high range) under the low TWPs scenario to between ~43 and 911 t under the high scenario, indicating substantial cumulative environmental loading.

Table 11. Amount of PAHs already released into the environment through TWPs (1980–2020).

Vehicle Category	Low TWPs Release Scenario		Mid TWPs Release Scenario		High TWPs Release Scenario	
	Low PAHs Release Scenario	High PAHs Release Scenario	Low PAHs Release Scenario	High PAHs Release Scenario	Low PAHs Release Scenario	High PAHs Release Scenario
Cars	6	131	8	160	10	218
Buses	10	223	18	372	30	620
Trucks	2	37	3	55	3	73
Total	18	391	29	587	43	911

Again, buses are the dominant source of PAHs, followed by cars and trucks, consistent with higher tyre wear rates and the presence of PAHs in tyre rubber formulations and carbon black fillers [10,66]. PAHs are well-established carcinogenic and mutagenic compounds [66], and their association with fine particulate matter enhances their environmental mobility and bioavailability.

The estimated PAH releases suggest that tyre wear may represent a significant non-exhaust source of PAHs [63,64] in Nigeria, potentially rivaling or augmenting contributions from fuel combustion, open burning, and industrial activities. Given Nigeria's dense urban centres and limited regulation of non-exhaust emissions, these results highlight TWPs as an important pathway for PAH exposure in both terrestrial and aquatic environments.

3.4.4. Data Validation, Limitations and Uncertainties

Validation measures included cross-checking number of vehicles POM and stock data with national transport registry reports; comparing replacement rates with tyre manufacturers' specifications and local vulcanizer surveys; consistency checks across the 40-year dataset.

Limitations include lack of a national tyre registry which may introduce uncertainties in local replacement patterns; informal imports of used tyres which are not officially documented, and disposal estimates which assume uniform tyre configurations across all subtypes. Motor vehicle crash records for each year under study are also not available. Despite these limitations, the combined dataset and assumptions provide a reliable national-scale assessment of tyre flows in Nigeria.

"Mass loss per tyre" is bulk tread/tyre mass lost during service; only a portion of that mass is in respirable PM ($PM_{2.5}$/PM_{10}). Literature shows <10% of tread mass loss may be in PM_{10} fraction in some studies; the remainder is coarser particles, road dust, or retained on surfaces [57]. So TPM as computed here is *total tyre material abraded* (all particle sizes), not $PM_{2.5}$ or PM_{10} exclusively. Lifetime wear depends strongly on mileage, driving behaviour, road surface and climate. Countries where vehicles drive more km per tyre will have greater lifetime wear; Nigeria's fleet usage patterns (urban congestion vs highway km) will alter the real totals. Tyre compound, tyre size, pressures, wheel alignment and tyre replacement practices affect wear rates. Heavy vehicles' tyres vary widely by axle configuration and duty cycle; bus and truck wear assumptions are approximate.

It is pertinent to note that not all abraded mass leaves the roadside environment immediately. Some particles become part of road dust and may be re-entrained or transported to storm drains; others remain near road edges. Our mass numbers represent *available* released mass, not instantaneous environmental concentration or fate.

3.5. Uncertainty Characterization

See supplementary material for the detailed discussion of the uncertainty characterization.

4. Discussion

4.1. Environmental Burden from Increasing Waste Tyre Generation and Disposal

Motor vehicle tyres are engineered from a complex mix of natural and synthetic polymers, reinforcing fillers, heavy metals, oils, and performance-enhancing additives. While these materials enable durability and road safety, they pose significant environmental and public health challenges throughout the tyre life cycle. Tyres consist of 40–60% rubber, including natural rubber and synthetic rubber such as styrene-butadiene rubber and butadiene rubber. During vehicle use, abrasion against road surfaces generates TWPs—a major global source of microplastics. TWPs consist of rubber fragments mixed with road dust and additives.

Environmental risks of TWPs include microplastic accumulation in soils, rivers, and marine ecosystems; long-term persistence, as synthetic rubber degrades extremely slowly; toxicity to aquatic organisms, especially bottom feeders and filter feeders; bioaccumulation of attached chemicals (e.g., PAHs, zinc, aromatic amines). TWPs enter the environment via stormwater runoff, wind dispersion, and direct deposition on road verges. Key environmental pathways are leaching from stockpiles during rainfall, release from TWPs on roads and drains, volatilization or decomposition during tyre burning, and migration into groundwater at dumpsites. The estimated approximately 776 million tyres (20,537 kt) reflect a substantial waste management challenge. Without formal recycling or collection systems, Nigeria's ELT burden manifests through stockpiling and open dumping of ELT**.** Waste tyres accumulate in urban centres, roadside dumps, market clusters, mechanic villages, and vacant lots. These stockpiles occupy valuable land, create fire hazards, provide breeding sites for mosquitoes and rodents, and contribute to urban drainage blockage and flooding.

The use of motor vehicles generates microplastics and TWPs, which accumulate in road dust, stormwater drains, rivers and coastal waters with associated pollutant release. This contributes to aquatic toxicity and long-term ecological risks.

Open burning remains the default waste management method in many Nigerian cities. Tyre combustion releases toxic emissions including PAHs, volatile organic compounds (VOCs), dioxins and furans, heavy metals such as zinc and cadmium, and carbon monoxide and the short-lived climate pollutant (SLCP) soot/black carbon. These hazardous emissions contribute to respiratory illnesses, endocrine disruption, and carcinogenic exposure among nearby populations as well as to global warming. Unfortunately, ELT are used in abattoirs to roast animal skin consumed by residents which is a particular exposure pathway. Carbon black (20–25% of tyre mass) increases tyre strength and wear resistance. It also contributes to black particulate matter ($PM_{2.5}$ and PM_{10}) when tyres burn; adsorbs organic pollutants that are released during degradation or combustion; increases urban "soot load" associated with respiratory diseases. In cities like Lagos and Port Harcourt, tyre burning contributes significantly to visible black smoke events.

4.2. Environmental Consequences

According to Christou et al. [67], the health consequences of chemicals released from used tyres arise mainly from exposure to complex mixtures of substances such as heavy metals (e.g., Zn, Cd, Pb), PAHs, benzothiazoles, and additives (e.g., 6-PPD derivatives). These substances can be released as fine particles or leachates and enter the human body via inhalation, ingestion, or dermal contact. The study highlights that such exposures are associated with respiratory inflammation, oxidative stress, endocrine disruption, and increased carcinogenic risk, especially due to PAHs and certain metals. Fine particulate matter from tyre wear can penetrate deep into the lungs, contributing to cardiopulmonary diseases, while some transformation products (e.g., 6-PPD quinone) exhibit acute toxicity to biological systems similar to challenges of microplastics [68].

From an environmental perspective, and consistent with the Basel Convention approach, the primary concern is not that tyres are inherently classified as hazardous waste, but that improper management leads to ecotoxicological impacts. Tyre-derived particles accumulate in soil, water, and air, releasing toxic chemicals that can harm aquatic organisms, disrupt microbial communities, and contribute significantly to heavy metal pollution (notably zinc) [67]. Leachates from tyre materials introduce persistent organic pollutants and additives into ecosystems, while uncontrolled disposal (e.g., open dumping or burning) can cause soil and groundwater contamination, air pollution, and toxic emissions. The Basel framework therefore emphasizes that risks are strongly linked to mismanagement, leaching, and environmental exposure pathways, rather than the bulk material itself, necessitating environmentally sound collection, recycling, and disposal practices.

4.3. Current Reuse Practices for ELTs towards Circularity

ELTs are reused in various applications in Nigeria by informal operators and by new start-ups. For instance Freee Recycle Limited, founded in 2018, recycles used tires by shredding them into rubber granules, mixing with adhesives, and moulding into durable products like interlocking paving bricks (and interlocking pavers for roads and driveways), floor tiles (Floor tiles and rubber mats for homes, offices, gyms, and playgrounds.), flip-flops, slippers, rubber mulch, and insulating materials [69,70]. Freee Recycle collect ELTs from dumpsites, vendors, and outlets in major cities of Nigeria (e.g., Lagos, Abuja, and Port Harcourt), and then process them to reduce waste in landfills, prevent illegal burning, which releases toxic smoke. This also eliminates breeding grounds for mosquitoes in stagnant water within discarded tyres, thus helping to control the spread of malaria.

There are indications that the company has retrieved over 600,000 ELTs, recycled more than 400,000 (with ambitious goal to recycle 5 million scrap tyres annually), and created over 150 jobs, mainly for women and youth, while offering cheaper, weather-resistant alternatives to concrete. The major environmental benefit of these activities is the prevention of over 8100 metric tons of carbon dioxide emissions. Freee Recycle believes it has prevented more than 8100 tonnes of CO_2 emissions since it began [70,71].

This circular model mitigates pollution from tire burning or dumping, which releases toxins like dioxins, and supports urban infrastructure needs with slip-resistant, shock-absorbent products. Freee Recycle's scalable approach has gained international recognition as a female-led innovation for sustainability in Africa.

The transformation of ELTs from an environmental burden into valuable resources presents significant socio-economic opportunities for Nigeria. With an estimated 19 million waste tyres (equivalent to 513 kt of waste tyres) generated annually, the country has one of the largest potential markets for tyre recycling, resource recovery, and green industry development in Africa. Considering large quantities of waste tyres generated annually, Nigeria can explore tyre recycling technologies and the opportunities they present including mechanical recycling (crumb rubber production) and tyre-derived fuel (TDF).

Mechanical recycling involves shredding, granulating, and grinding tyres into smaller rubber fragments, known as *crumb rubber* or *rubber granulate*. Key products include crumb rubber (0.5–2 mm), rubber chips (10–20 mm), steel wire (recovered from beads and belts), textile fibres. The applications are: one, construction and infrastructure (rubberized asphalt (increases road durability), interlocking bricks and paving tiles, floor tiles and roofing materials, vibration-damping pads for rail lines); two, sports and recreation (playground surfacing, synthetic turf infill, running tracks, gym flooring); three, industry (rubber mats, conveyor belts, impact-absorbing materials). The economic prospects include high demand in construction and urban development. Local manufacturing can reduce reliance on imported floor tiles and paving stones. There is job creation in collection, shredding, and processing. Nigeria's booming real estate market makes crumb rubber a high-potential product.

Tyres have a high calorific value (32–34 MJ/kg), comparable to coal [72]. When used in controlled industrial settings, tyre-derived fuel can safely replace traditional fossil fuels. Industries suited for TDF are cement kilns, steel mills, power plants, and brick factories.

4.4. Limitations of Nigeria's Current ELT Management Framework

Nigeria had a framework for waste tyre management—the National Environmental (Tyre and Battery Waste Control) Regulations, 2009. Even with regulatory provisions, there still exists several challenges in implementing ESM for waste tyres in Nigeria. These challenges can be broadly grouped into 4 (i) weak enforcement of existing regulations (ii) absence of EPR for end-of-life tyres, (iii) lack of formal recycling markets, and (iv) heavy dependence on informal sector.

Environmental regulations in Nigeria, overseen by agencies like NESREA, are rarely enforced at high-pollution sites such as dumpsites, mechanic workshops, auto-markets, and abattoirs (where waste tyres are used to roast cow), where waste tyres accumulate without oversight. This stems from limited resources, poor coordination, and data gaps, allowing open dumping and burning that clogs drains and heightens flood risks in big cities like Lagos and Port Harcourt. Strengthening enforcement requires better funding and monitoring to curb these practices effectively.

Nigeria currently lacks a mandatory EPR framework for ELT, leaving importers, marketers, and transport operators free from obligations to collect, recycle or properly dispose ELT. While NESREA signed an agreement with Used Tyres Producer Responsibility Organisation (UTPRO) in 2023 to advance EPR-like measures to enforce proper management of over 10 million end-of-life tyres generated annually in the country, UTPRO acts as a third-party PRO to implement waste management programs, traceability, and compliance with regulations like the National Environmental (Domestic and Industrial Plastic, Rubber, and Foam sector) Regulations where ELTs are encapsulated [9]. However, there is no binding national scheme that enforces take-back or recycling yet. Consequently, the estimated 19 million units or 513 kt ELTs enter the waste stream annually without traceability, amplifying environmental harm.

Small-scale artisans in Nigeria are creatively repurposing waste tyres into useful products like rubber paving stones (durable, eco-friendly flooring for schools, fitness facilities), mats and tiles (crushed tyres + bonding agents), upcycled flip flops (eco-friendly, some with Nigerian cultural designs; buckets, sandals, and furniture), and steel products (smelted scrap metal for nails, wire, etc.). Unfortunately, there are no structured formal markets exist to scale this up. This limits absorption of the roughly huge amounts of ELT discarded yearly, as most end up in unregulated dumps or burned. Developing formal markets demands investment in advanced recycling technologies and incentives to process larger volumes sustainably.

The informal sector dominates tyre repairs, vulcanization, used tyre sales, and artisanal recycling in Nigeria, yet it operates without capacity for large-scale ELT management or proper infrastructure. These operators contribute to uncontrolled disposal, exacerbating pollution, health risks like cholera outbreaks, and urban flooding. Transitioning requires formalizing operations through policy support, training, and partnerships to mitigate the escalating environmental threats without swift intervention.

4.5. Need for Regulatory Framework and Tyre Waste Management Strategy

The study's findings of high release of hazardous additives including POPs from tyres and the frequent open burning but also the providence of breeding grounds for vectors, underscore the urgent need for Nigeria to adopt: a national ELT collection network; pyrolysis and mechanical recycling plants; reforms in vehicle and tyre import policies; economic incentives for tyre retreading; circular economy frameworks. The integration of these strategies is essential to prevent growing pollution, improve public health outcomes, and generate new green economic opportunities. Additionally, it calls for the substitution of hazardous additives from this emission prone product.

A mandatory EPR scheme for tyres would: require importers and manufacturers to collect and recycle ELTs; fund nationwide collection networks; promote producer accountability; ensure environmentally sound management. The National Environmental (Tyre and Battery Waste Control) Regulations, 2009 must be enforced through regular inspections, targeted penalties, licensing of tyre recycling companies, and monitoring the ban unhealthy practices where butchers use waste tyres for roasting animal skin in abattoirs.

The assumption that all tyres are equal or that used tyres are "good enough" increases the risk of accidents and contributes to pollution through tyre debris. Improper disposal of worn tyres also poses significant environmental challenges. Promoting awareness on proper tyre configuration, utilisation of quality tyres, and support for safe disposal and recycling practices can enhance safety and sustainability on Nigerian roads. Policy interventions can play a crucial role in driving these improvements.

5. Conclusions

This study provides the first systematic material flow analysis of motor vehicle tyres in Nigeria, establishing the substantial and growing environmental burden posed by ELTs and their embedded chemical contaminants. The quantitative findings underscore a national waste management crisis driven by a rapidly expanding vehicle fleet and inadequate regulatory infrastructure. The annual generation of about 19 million units or 513 kt ELTs is the most critical figure, demonstrating the urgent need for a structured disposal pathway. This waste is not only a physical eyesore but a vector for toxic chemical contamination, particularly from CPs, which enter the environment through open dumping, leaching, and uncontrolled burning. Nigeria's rapid vehicle fleet expansion over the past four decades has led to significant increases in tyre consumption and waste generation. This study estimated that approximately 98 million tyres were introduced into the Nigerian market between 1980 and 2020, with 776 million tyres used within the period of 40 years. The annual generation of waste tyres is high (19 million tyres/year).

This study demonstrates that tyre wear has likely contributed substantial historical loads of CPs, 6PPD, and PAHs to the Nigerian environment over the past four decades. Heavy-duty vehicles consistently emerge as the primary contributors across all pollutants and scenarios. These findings align with international studies identifying TWPs as a major source of persistent and toxic organic contaminants [10,64] and emphasise the need to incorporate non-exhaust emissions into environmental risk assessments, transport policies, and pollutant monitoring frameworks, particularly in rapidly motorising countries such as Nigeria.

The environmental impacts associated with tyres are profound and occur throughout their life cycle. Tyre wear releases microplastics, chemical additives, and particulate pollutants, while improper disposal leads to drainage blockage, flooding, open burning emissions, soil and water contamination, disease vector breeding, and long-term landscape degradation. Nigeria's dependence on imported used tyres increases replacement rates, accelerating tyre waste generation. Despite the existence of national regulations, tyre waste management in Nigeria remains largely informal, with weak enforcement, inadequate recycling infrastructure, limited public awareness, and absence of EPR. However, significant circular economy opportunities exist in mechanical recycling, pyrolysis, retreading, tyre-derived fuel, and manufacturing of rubberized construction materials. These pathways offer major economic, environmental, and social benefits—ranging from job creation to import substitution, resource recovery, and reduced urban pollution.

To address the current crisis, Nigeria must urgently implement a national ELT management framework that integrates policy reforms, investment incentives, enforcement mechanisms, environmental monitoring, and active participation of the private and informal sectors. Transitioning to a circular economy for tyres will not only reduce pollution but also unlock new green industrial opportunities essential for sustainable development.

Supplementary Materials

The additional data and information can be downloaded at: https://media.sciltp.com/articles/others/2605111013285661/ECCS-26010168-SM.pdf.

Author Contributions

J.O.B.: conceptualization, methodology, software, data curation, writing—original draft preparation; I.C.N.: visualization, investigation, validation, writing—reviewing and editing; R.W.: supervision, validation, writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

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The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used ChatGpt for review of literatures and in the study of uncertainties. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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