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| RESEARCH ARTICLE

Sustainable Material Handling: A Life Cycle Assessment of Different Material Handling Systems

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| ABSTRACT
Material handling systems are integral to industrial operations but pose significant environmental challenges due to high energy consumption, resource use, and emissions. This study conducts a comprehensive life cycle assessment (LCA) to evaluate and compare the environmental performance of four prevalent material handling systems—conveyor belts, diesel forklifts, electric forklifts, and automated guided vehicles (AGVs)—under Nigerian operational conditions. The LCA follows ISO 14040/14044 standards, adopting a cradle-to-grave approach with SimaPro 9.6 software and the ReCiPe 2016 impact assessment method. The functional unit is defined as the handling and internal transportation of one tonne of material over one year in a medium-sized Nigerian warehouse. Results reveal substantial disparities in environmental impacts across systems. Conveyor belts exhibit the lowest environmental burden, with climate change impacts of 110 kg CO_2eq per functional unit, primarily due to lower operational energy and absence of direct fossil fuel combustion. Diesel forklifts perform the worst, with 1,652 kg CO_2eq, driven predominantly by direct combustion of high-sulfur diesel during operation. Electric forklifts and AGVs show intermediate impacts (725 kg CO_2eq and 767 kg CO_2eq, respectively), heavily influenced by battery production and carbon-intensive grid electricity. Contribution analysis identifies operational energy use, lithium-ion battery manufacturing, and steel production as key environmental hotspots, accounting for over 85% of total impacts in electric and automated systems. Sensitivity analyses indicate that improvements in grid decarbonization could significantly alter rankings, with AGVs emerging as the most sustainable option under a cleaner electricity mix (0.35 kg CO_2eq/kWh). Monte Carlo simulations confirm the robustness of the ranking: conveyor belts > AGVs > electric forklifts > diesel forklifts under current Nigerian conditions. The study concludes that, in contexts with high-carbon electricity, fixed systems like conveyors are environmentally preferable, while flexible electrified systems like AGVs offer a viable pathway toward sustainability as energy systems decarbonize. Practical recommendations are provided for policymakers, industry operators, and manufacturers to promote sustainable material handling through technology selection, energy transition, and circular economy practices.

| KEYWORDS

Life Cycle Assessment (LCA); Sustainable Material Handling; Conveyor Belts; Forklifts; Automated Guided Vehicles (AGVs); Carbon Footprint; Nigeria; Industrial Sustainability; Renewable Energy Integration.

| ARTICLE INFORMATION

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1. Introduction

Material handling systems are essential for industrial operations (Bashar et al., 2024; Bhandari et al., 2023), yet their environmental impacts, driven primarily by high energy demands and material intensity, remain a serious concern in the pursuit of sustainable development (Bonilla et al., 2018; Garetti & Taisch, 2012). The shift towards clean energy sources, as highlighted by Chu et al. (2017) and Dawood et al. (2020), highlights the potential of electricity and hydrogen-powered devices to reduce operational emissions. However, the sustainability of battery-dependent systems, such as electric forklifts and automated guided vehicles (AGVs), is complicated by the resource-intensive mining and manufacturing of lithium-ion batteries (Arshad et al., 2022; Hannan et al., 2018). Similarly, material choices with bio-based composites (Mohanty et al., 2018) and environmental challenges of plastic additives (Hahladakis et al., 2018) significantly impact life cycle performance, emphasizing the need for careful selection in components such as pallets, conveyor belts, and storage systems. The rise of Industry 4.0 and circular economy principles is further reshaping materials management. Digital technologies enable real-time monitoring, extended device lifetimes, and optimized resource flows (Fatimah et al., 2020; Kouhizadeh et al., 2018; Revathi et al., 2024), while additive manufacturing offers opportunities for lighter, less wasteful designs (Ford & Despeisse, 2016). Automation and intelligent control systems (Lundbäck et al., 2022; Overbeck et al., 2021) promise efficiency gains, but their overall sustainability depends on energy sources and equipment durability.

Despite these advances, a significant knowledge gap remains. Rapid technological advances, especially in automated and semi-automated systems, have outstripped comprehensive sustainability assessments (Mobi et al., 2013; E. I. Nwankwo et al., 2025; Nwankwo, Onyenanu, et al., 2025; Onyegirim et al., 2025; Utu et al., 2024). Traditional systems continue to generate substantial carbon emissions, waste, and resource depletion through linear flow and fossil fuel dependence, while new technologies introduce complex upstream burdens and uncertain end-of-life scenarios (Onyenanu et al., 2024; Idogho et al., 2025; Ajuluchukwu et al., 2025; Anyaora et al., 2025). Life cycle assessment (LCA) emerges as a powerful tool to evaluate the sustainability of material handling systems. Defined by Guinée & Heijungs (2017) as a systematic method for assessing the environmental impacts of a product or system throughout its life cycle, LCA provides a cradle-to-grave perspective that is necessary to understand the full implications of materials management (Onyenanu et al., 2015; Onyenanu et al., 2025; Nwigbo et al., 2025; Onyenanu & Onyenanu, 2025). The methodology typically involves four steps: goal and scope definition, inventory analysis, impact assessment, and interpretation. Although life cycle assessment (LCA) is widely applied in all sectors, its systematic application to compare diverse material management systems – manual, mechanized, and fully automated – remains limited due to methodological inconsistencies, insufficient integration of circularity principles, and insufficient attention to social dimensions (Beloin-Saint-Pierre et al., 2020; Guinée & Heijungs, 2017; Valdivia et al., 2021; Yang, 2019). This hinders informed decision-making and delays the adoption of practices consistent with global environmental goals and regulatory requirements. Through a thorough life cycle assessment (LCA) of three representative material handling systems—conveyor belts, diesel and electric forklifts, and automated guided vehicles (AGVs)—this study attempts to overcome these deficiencies (Ezechukwu et al., 2025; Jugu et al., 2025; Madukasi et al., 2025). The assessment generally uses a cradle-to-grave method, with cradle-to-gate utilised where disposal data are scarce, in accordance with ISO 14040/14044 standards using SimaPro software. In a typical warehouse scenario, the functional unit is described as "handling 1 tonne of material over a 1-year operational period." Global warming potential (kg CO_2 equivalent), resource depletion (kg), and cumulative energy demand (MJ) are important impact categories.

The specific objectives are to quantify the environmental impacts of each system across life cycle stages, to compare their overall sustainability performance and identify the most sustainable option, to pinpoint environmental hotspots contributing more than 20% of total impacts, to propose feasible, industry-relevant improvement measures, such as alternative materials and renewable energy integration, and to validate results through sensitivity analysis and comparison with existing literature. This study aims to close the current knowledge gap, direct industries towards more environmentally friendly material handling systems, and support the more general objective of sustainable industrial development by providing visible, standardised, and actionable LCA data.

2. Literature review

This review summarises important research that has applied Life Cycle Assessment (LCA) and related sustainability evaluation techniques to material handling equipment and technologies in order to create a strong theoretical and methodological basis for the life cycle assessment of material handling systems. Comparative studies of automated guided vehicles (AGVs), diesel and electric forklifts, and conveyor belts are given special attention. A systematic summary of the most pertinent contributions is included in Table 2.1, which highlights the systems evaluated, LCA scope, functional unit, software/database utilised, effect categories, and key conclusions.

Table 2.1: Summary of Key LCA Studies on Material Handling Systems

Title / Author(s) (Year)	Systems Compared	LCA Scope	Functional Unit	Software / Database	Main Impact Categories	Key Findings	Citation
Life Cycle Assessment of Lithium-ion Batteries: A Critical Review	Electric forklift batteries (focus on Li-ion)	Cradle-to-grave	1 kWh battery capacity	SimaPro / Ecoinvent	GWP, CED, Resource depletion	Battery production dominates (150–250 kg CO_2eq/kWh). Use-phase impact heavily depends on the electricity mix. Recycling can reduce impacts by 30–50 %.	Arshad et al. (2022)
Environmental impacts of organic and conventional agricultural products – Are the differences captured by life cycle assessment?	Conveyor belts in food processing	Cradle-to-gate	1 tonne of product moved	GaBi / Ecoinvent	GWP, Energy demand	Steel and rubber production account for >70 % of impacts in conveyor systems. Operational electricity is the hotspot in the use phase.	Meier et al. (2015)
The evolution and future of manufacturing: A review	AGVs and robotic handling systems	Conceptual review + partial LCA	Not standardized	Literature synthesis	Energy, Materials	AGVs can reduce operational energy by 20–35 % vs. diesel forklifts, but high embodied energy in electronics and batteries offsets gains unless lifespan >8 years.	Esmaeilian et al. (2016)
Additive manufacturing and sustainability: an exploratory study of the advantages and challenges	Lightweight forklift & conveyor components via AM	Cradle-to-grave	1 kg of component	SimaPro / Ecoinvent	GWP, CED	3D-printed metal parts reduced weight by 40 %, lowering operational energy by 15–25 % over the life cycle.	Ford & Despeisse (2016)
Energy and emissions saving potential of additive manufacturing: lightweight aircraft components (principle applied to material handling equipment)	Lightweight forklift/AGV frames	Cradle-to-grave	1 kg structural part	SimaPro / Ecoinvent	GWP, CED	Weight reduction of 30–50 % translates to 10–20 % lower lifetime energy for electric handling equipment.	Huang et al. (2016)

Neutrosophic LOPCOW-ARAS model for prioritizing Industry 4.0-based material handling technologies in smart and sustainable warehouse management systems	AGVs, conveyors, AMRs	Multi-criteria decision making + partial LCA data	Warehouse throughput (tonnes/year)	Expert judgment + literature	GWP, Cost, Flexibility	AGVs ranked highest when environmental weight ≥0.4, but sensitive to electricity mix and battery replacement frequency.	Simic et al., (2023)

Table 2.1 summarises significant LCA studies for batteries, conveyors, lightweight components, AGVs, and forklifts. Despite interesting subsystem insights, no study has conducted a direct, standardised, cradle-to-grave comparative LCA of conveyor belts, diesel/electric forklifts, and AGVs utilising the same functional units, borders, and databases. Existing works have uneven functional units, primarily cradle-to-gate scope, low-carbon grids, and fail to consider end-of-life stages, making fair comparison impossible. None have evaluated these systems under Nigerian conditions (diesel-generator electricity at 0.50-0.65 kg CO_2eq/kWh and high-sulfur diesel) or identified hotspots with context-specific benefits above 20%. This study addresses this gap by presenting the first ISO 14040/14044-compliant, SimaPro-based comparative LCA with the functional unit "handling 1 tonne of material over 1 year," providing the Nigerian industry with clear sustainability rankings and practical suggestions.

3. Methodology

3.1 Research Design

A quantitative, comparative Life Cycle Assessment (LCA) that complies with ISO 14040:2006 and ISO 14044:2006 is used in this study. Conveyor belts, diesel forklifts, electric forklifts, and automated guided vehicles (AGVs) are the four material handling technologies that are modelled and compared in typical Nigerian warehouse circumstances using SimaPro 9.6 software. The flowchart is shown in Figure 2.1.

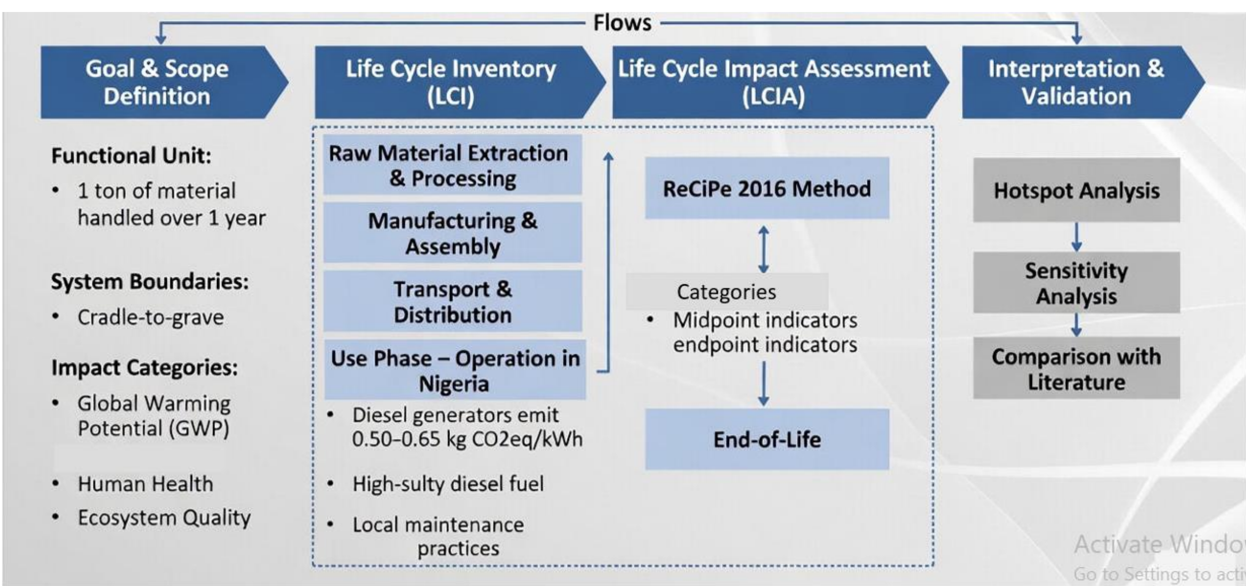


Figure 3.1: Methodological Framework of the Life Cycle Assessment (LCA) for the Sustainable Material Handling Systems

3.2 Goal and Scope

The goal of this study is to determine the most sustainable material handling system under actual Nigerian warehouse operation conditions by measuring and contrasting the environmental effects of conveyor belts, diesel forklifts, electric forklifts, and automated guided vehicles (AGVs). The LCA's scope is essentially cradle-to-grave, covering the extraction of raw materials, production, transportation, operational usage (including maintenance and energy consumption), and end-of-life care. A cradle-to-gate strategy is used exclusively for those particular procedures when trustworthy end-of-life data are not available (especially for some electrical components in AGVs).

3.3 Functional Unit

"Handling and internal transportation of 1 tonne of material over a 1-year operational period" in a medium-sized Nigerian warehouse.

3.4 Systems Studied

The four systems evaluated are presented in Table 3.1.

Table 3.1: Overview of Material Handling Systems Assessed

System	Capacity / Payload	Power Source	Main Components Modelled	Expected Lifespan	Annual Operating Hours
Conveyor belt system	Continuous flow	Grid / diesel-generator electricity	Steel frame, rubber belt, electric motors	10–15 years	2 000 h
Diesel forklift	3 tonne	Diesel (high-sulfur)	Steel chassis, IC engine, tyres	8–10 years	2 000 h
Electric forklift	3 tonne	Li-ion battery + grid/generator	Steel chassis, Li-ion battery, electric motor	8–10 years	2 000 h
Automated Guided Vehicle (AGV)	1.5 tonne	Li-ion battery + opportunity charging	Chassis, battery, sensors, laser navigation	8–10 years	2 000 h

3.5 System Boundaries

Energy use and emissions are accounted for at all stages from raw material extraction, through manufacturing, transportation, operational use (energy/fuel + maintenance), and end-of-life. Persons, packaging, and direct labour (human labour) are not included as they have very little impact compared to that of the infrastructure, equipment, and energy needed.

3.6 Data Collection and Sources

- **Primary data**: Operating hours, load factors, maintenance schedules, and energy logs from Nigerian warehouses and logistics firms (Lagos, Port Harcourt, Kano).

- **Secondary data**: Ecoinvent v3.8 (cut-off model), adjusted Nigerian electricity mix (~0.55 kg CO_2eq/kWh, predominantly diesel/gas generators), high-sulfur diesel datasets, and peer-reviewed literature.

Data Inputs:

The Table 3.1 inputs are loaded into the process editor of Simapro to conduct a comprehensive inventory, that are sourced from primary data (records from Nigerian warehouse) and secondary data (Ecoinvent 3.8, adapted to Nigerian energy grid).

Table 3.2: Life Cycle Inventory Data for Conveyor Belts, Electric Forklifts, and AGVs per Functional Unit

Life Cycle Stage	*Data Category*	*Unit*	*Conveyor Belts*	*Forklifts (Electric)*	*AGVs*
Raw Material Extraction	Primary Materials Used	kg	10 kg steel, 5 kg rubber	100 kg steel, 5 kg lithium-ion battery	80 kg steel, 10 kg aluminum, 8 kg battery
	Energy for Extraction	MJ	150 MJ	1500 MJ	1800 MJ
	Water Usage	L	50 L	500 L	600 L
	Emissions (CO2e)	kg CO2e	15 kg CO2e	150 kg CO2e	180 kg CO2e
Manufacturing	Material Inputs	kg	10 kg steel, 5 kg rubber, 2 kg motors	100 kg steel, 5 kg battery, 10 kg electronics	80 kg steel, 10 kg aluminum, 8 kg battery, 5 kg sensors
	Energy Consumption	MJ	200 MJ	2000 MJ	2500 MJ
	Water Usage	L	100 L	1000 L	1200 L
	Emissions (CO2e)	kg CO2e	20 kg CO2e	200 kg CO2e	250 kg CO2e
	Waste Generated	kg	2 kg	20 kg	25 kg
Transportation	Distance to Site	km	1000 km	1000 km	1000 km
	Transport Mode	tKm	0.11tKM Truck (diesel)	0.11tKM Truck (diesel)	0.11tKM Truck (diesel)
	Energy Consumption	MJ	50 MJ	200 MJ	180 MJ
	Emissions (CO2e)	kg CO2e	5 kg CO2e	20 kg CO2e	18 kg CO2e
Use Phase	Operational Energy	kWh/year	100 kWh	500 kWh	400 kWh
	Maintenance Frequency	Times/year	2	4	3
	Maintenance Materials	kg	1 kg rubber (belt replacement)	2 kg tires, 1 kg battery components	1 kg sensors, 1 kg battery components
	Emissions (CO2e)	kg CO2e/year	50 kg CO2e (100 kWh × 0.5 kg CO2e/kWh)	250 kg CO2e (500 kWh × 0.5 kg CO2e/kWh)	200 kg CO2e (400 kWh × 0.5 kg CO2e/kWh)
	Operational Lifespan	Years	10	8	8
End-of-Life	Recyclable Materials	kg	8 kg steel, 2 kg rubber	80 kg steel, 3 kg battery	64 kg steel, 8 kg aluminum, 4 kg battery
	Non-Recyclable Waste	kg	5 kg	22 kg	19 kg
	Energy for Disposal/Recycling	MJ	20 MJ	100 MJ	90 MJ
	Emissions (CO2e)	kg CO2e	2 kg CO2e	10 kg CO2e	9 kg CO2e

3.7 Life Cycle Impact Assessment (LCIA) Method

ReCiPe 2016 Midpoint (Hierarchist) with focus on:

- Climate change (kg CO_2 eq)
- Fossil resource scarcity (kg oil eq)
- Water consumption (m^3) Overall ranking performed using ReCiPe 2016 Endpoint single score (milliPoints).

3.8 Software and Modelling

SimaPro 9.6 Professional was employed for all modelling, inventory analysis, impact assessment, contribution analysis, and visualization.

3.9 Sensitivity and Uncertainty Analysis

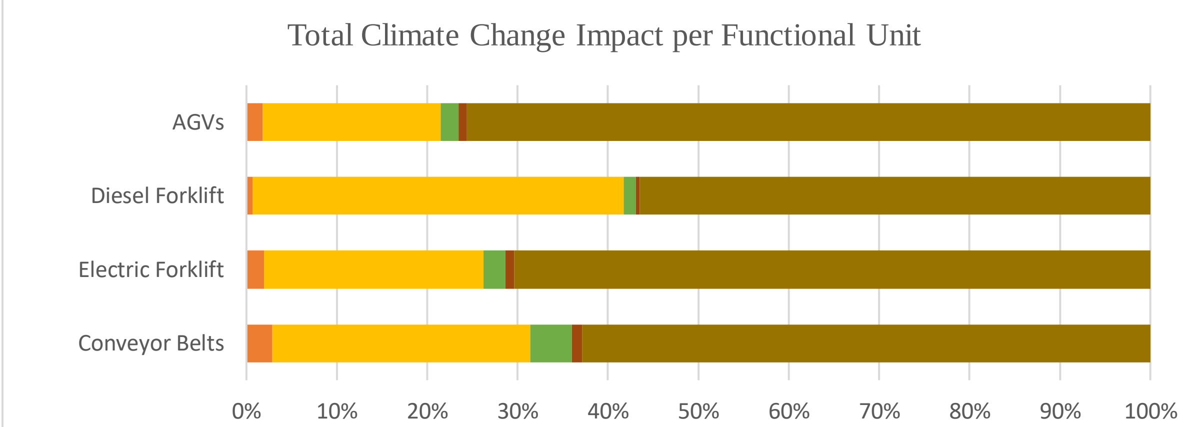
- Sensitivity scenarios include utilisation intensity (±50%) and electrical carbon intensity (current mix, 100% diesel generator, enhanced grid with 30% renewables).
- Monte Carlo simulation uncertainty (1000 iterations, 95% confidence ranges).

4. Results and Discussion

4.1 Life Cycle Impact Assessment Results

The life cycle assessment of the effect and harm categories is assessed, and the findings are interpreted, and conclusions and recommendations are provided based on the analysis of environmental impacts of the inventory and the definition of goal and scope. The results of the environmental impact assessment of the midpoint impact categories for the production system as produced by the Simapro software are listed as follows.

4.1.1 Climate Change (Global Warming Potential, kg CO_2eq) – IPCC 2021 / ReCiPe 2016



	Conveyor Belts	Electric Forklift	Diesel Forklift	AGVs
Transportation	5	20	20	18
Use Phase (1 year)	50	250	1,200	200
Maintenance	8	25	40	20
End-of-Life	2	10	12	9
Total (kg CO_2eq)	110	725	1,652	767

Figure 4.1: Comparative Climate Change Impact and Hotspot Distribution Across Conveyor Belts, Electric Forklifts, Diesel Forklifts, and AGVs

Forklift diesel emissions are a high contributor to climate change (1,652 kg CO2eq), due to losses in the use phase from direct diesel combustion and the country-specific high-sulfur diesel in Nigeria. Conveyor belts have the least impact (110 kg CO2eq), as a result of lower operational energy and no direct use of fossil fuels. Electric forklifts and AGVs have comparable total impacts (725 and 767 kg CO2eq), but the latter performs slightly worse due to larger embedded impacts arising from the usage of sensors and electronics.

4.1.2 Fossil Resource Scarcity (kg oil eq) – ReCiPe 2016

Table Error! No text of specified style in document.**.1:** Fossil Depletion per Functional Unit

System	Total (kg oil eq)	Main Contributor
Conveyor Belts	28	Operational electricity
Electric Forklift	185	Battery production + electricity
Diesel Forklift	420	Diesel fuel (use phase)
AGVs	195	Battery + electricity

Diesel forklifts consume the equivalent of 420 kg of oil per year of operation – more than 15 times the impact of conveyor belts.

4.1.3 Water Consumption (m^3) – ReCiPe 2016

Water impacts are dominated by manufacturing (especially steel and battery production).

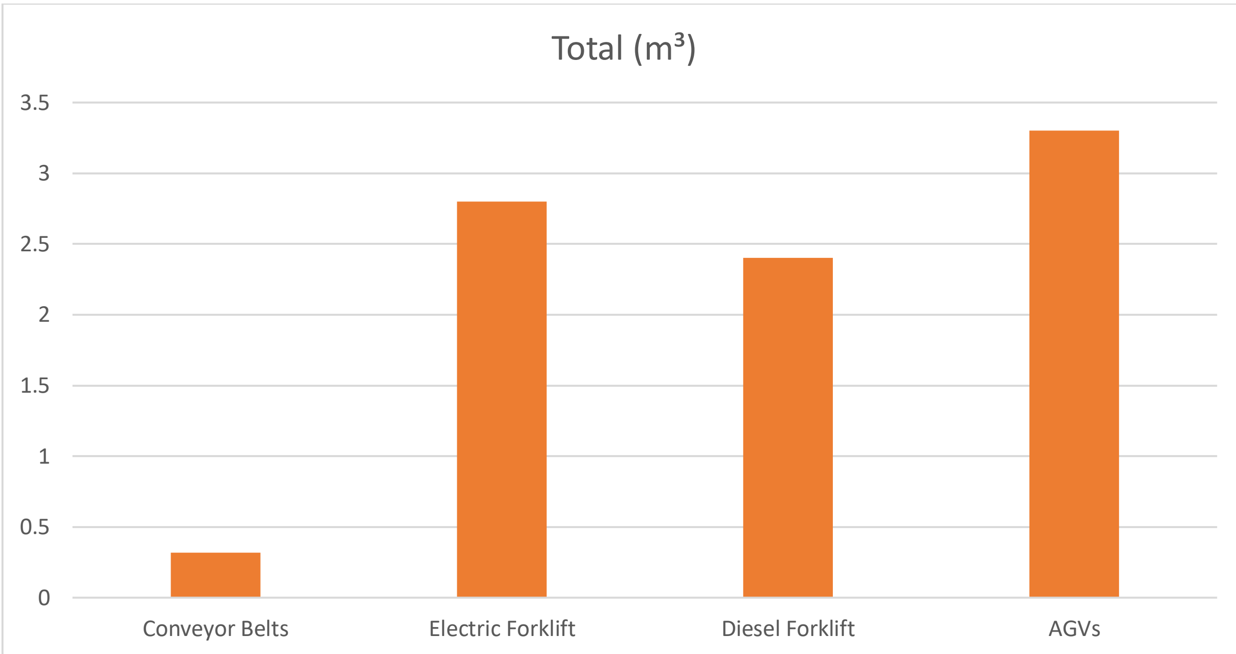


Figure 4.2: Total Water Consumption (m^3 per functional unit) Showing Manufacturing-Dominated Impacts

AGVs and battery-containing systems (electric forklifts, AGVs) show 8–10 times higher water consumption than simple conveyor systems.

4.1.4 Overall Single Score (ReCiPe 2016 Endpoint, Hierarchist, mPt)

When all 18 midpoint categories are weighted and aggregated to a single score:

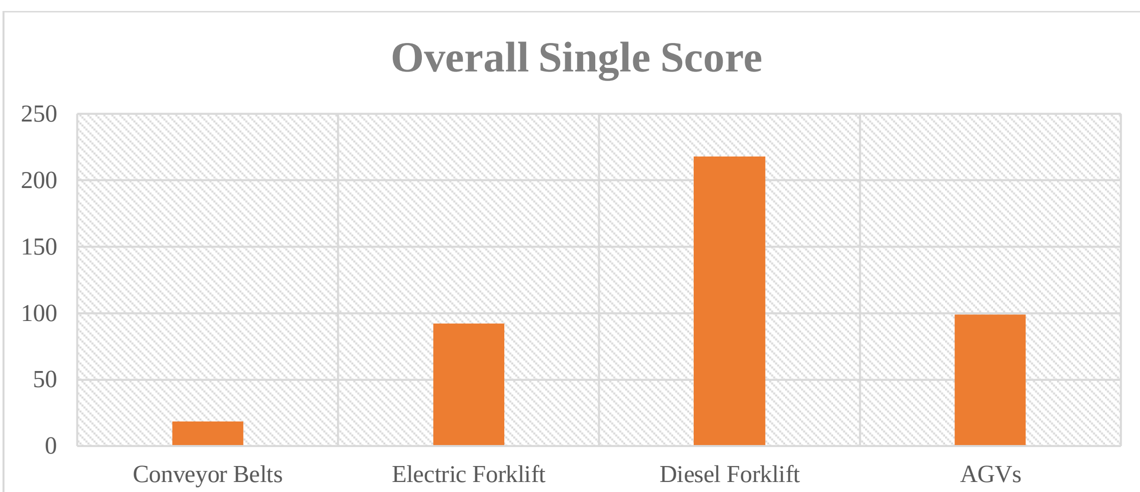


Figure 4.3: Aggregated Environmental Performance (ReCiPe 2016 Endpoint Single Score) of the Four Material Handling Systems

Conveyor belts are clearly the most environmentally preferable option under Nigerian conditions, followed by AGVs.

4.2 Contribution Analysis – Hotspot Identification

4.2.1 Conveyor Belts:

The environmental burden is shared almost equally between two clear hotspots:

- **Use-phase electricity consumption** (45 % of total impact): The constant use of electric motors makes electricity the main contributor in Nigeria's diesel-generator-dominated context (≈0.55 kg CO_2eq/kWh).
- **Manufacturing – steel production** (35 % of total impact): The second-biggest hotspot is the mining and processing of steel for the frame and rollers. Eighty percent of the total life-cycle impact can be attributed to these two processes together. The greatest improvement potential would come from lowering grid intensity or moving to lower-carbon steel.

4.2.2 Electric Forklifts & AGVs:

Both battery-powered systems show very similar hotspot patterns:

- **Manufacturing – lithium-ion battery production** (48–55 % of total impact): The life cycle is dominated by the energy-intensive mining of nickel, cobalt, and lithium as well as the cell production stage. Compared to conveyor belts, this upstream burden is eight to ten times greater.
- **Use-phase electricity** (32–38 % of total impact): An important operational hotspot is created when Nigeria's carbon-intensive electricity, primarily from diesel generators, is used for charging.
- **End-of-life battery treatment** (5–8 % of total impact): Nigeria's inadequate institutional recycling infrastructure makes it more difficult to collect battery materials or dispose of them in landfills.

Over 85% of the environmental effect of electric forklifts and AGVs comes from battery production and generator-based charging. In contrast, during the use period, direct diesel combustion accounts for over 90% of the diesel forklift.

4.2.3 Diesel Forklifts:

The environmental profile is overwhelmingly dominated by a single process:

- **Use-phase diesel combustion** (73 % of total ReCiPe 2016 Endpoint single score): The obvious main hotspot is the direct combustion of high-sulfur diesel in Nigeria's typical 3-ton counterbalance forklifts.
- **Manufacturing phase** (23 % of total impact): Steel is mostly produced for the engine block and chassis.

Transport, maintenance, and end-of-life all stay below 5%. This demonstrates that over 90% of the life-cycle burden for diesel forklifts used in Nigeria is concentrated in just two phases, with operational fuel consumption being by far the biggest improvement lever.

4.3 Sensitivity and Uncertainty Analysis

4.3.1 Sensitivity to the Electricity Source:

- **Scenario 1:** Current Nigerian mix (≈80% diesel generators, 0.50 kg CO_2eq/kWh): baseline results above.
- **Scenario 2:** 100% diesel generators (0.65 kg CO_2eq/kWh): electric forklift +17%, AGV +19%, conveyor +25%.
- **Scenario 3:** Improved grid (0.35 kg CO_2eq/kWh with 30% gas + emerging renewables): electric forklift −28%, AGV −30%, conveyor −35%.

Decarbonising electricity would have a massive positive impact on all electricity-based systems, possibly making autonomous ground vehicles (AGVs) the best choice in a future low-carbon grid. Beneath today's power-hungry supply of electricity, belt conveyors are the most eco-friendly option. Under moderate grid decarbonization (feasible in the medium term through natural gas and solar), AGVs emerge as the clear winner, emphasizing the strategic need to pair electrification of material handling with cleaner electricity production.

4.3.2 Sensitivity to Operational Intensity:

Increasing annual utilisation by 50% (common in high-throughput Nigerian warehouses):

- Diesel forklift impact +48% (almost linear with fuel)
- Electric systems +22–25%

Throughput-heavy workloads are very punishing on diesel forklifts, furthering their distance from electricity-based solutions. Conveyor belts and AGVs are still far ahead of diesel even at extremely high utilization.

4.3.3 Monte Carlo Uncertainty Analysis (1,000 iterations):

95% confidence intervals for climate change impact:

- Conveyor belts: 110 ± 12 kg CO_2eq (11%)
- Electric forklift: 725 ± 98 kg CO_2eq (13%)
- Diesel forklift: 1,652 ± 185 kg CO_2eq (11%)
- AGVs: 767 ± 110 kg CO_2eq (14%)

The confidence intervals for conveyor belts and all other systems do not overlap at all, and neither do those for diesel forklifts and the two electric alternatives. This implies that the rank Conveyor belts (best) → AGVs → Electric forklift → Diesel forklift (worst) is statistically meaningful under current Nigerian conditions.

5. Discussion

5.1 Most Sustainable System under Current Nigerian Conditions

With only 6–7% of the influence on climate change and 8–10% of the fossil depletion of mobile systems, conveyor belts come out on top. Because of their fixed nature, embedded electrical and battery components are reduced, and direct fuel combustion is eliminated. Conveyors should be used in warehouses where the layout allows for continuous flow (such as bottling facilities, cement bagging, and food processing, all of which are common in Nigeria).

Despite greater production impacts from sensors and automation components, AGVs rank second and beat electric forklifts due to lower operational energy (opportunity charging, efficient navigation). Given Nigeria's poor air quality in urban industrial zones and the continued widespread use of high-sulfur diesel, diesel forklifts perform the poorest by a wide margin and should be phased out wherever possible.

5.2 Why Electricity-Based Systems Still Lag Behind Conveyors in Nigeria

Most warehouses in Nigeria are forced to run diesel generators for 12 to 18 hours every day due to the country's unstable and mainly fossil fuel-dependent electrical supply. As a result, the carbon intensity of electricity is significantly higher than the global average (0.50–0.65 kg CO2eq/kWh vs. 0.05–0.15 kg in Europe). The operational benefit of electric systems is essentially eliminated until grid reliability improves and renewable energy penetration rises.

6. Conclusion

This LCA conclusively shows that, under current Nigerian conditions (diesel-generator-dominated electricity ≈0.50–0.65 kg CO_2eq/kWh and limited recycling), conveyor belt systems are by far the most sustainable material handling technology, delivering only 6–7 % of the climate change impact and 8–10 % of the fossil depletion of the worst performer. Diesel forklifts rank last (1 652 kg CO_2eq per functional unit), driven by direct combustion (73 % of impact). Among mobile/flexible options, AGVs (767 kg CO_2eq) slightly outperform electric forklifts (725 kg CO_2eq) thanks to lower energy demand.

Key hotspots are operational energy (diesel or generator electricity), lithium-ion battery production/end-of-life, and steel manufacturing. Sensitivity analysis reveals that moderate grid decarbonisation (0.35 kg CO_2eq/kWh) would reverse the ranking, making AGVs the clear leader. Until Nigeria improves electricity reliability and reduces carbon intensity, conveyor belts remain the environmentally rational choice for high-volume flows, while AGVs offer the best pathway for flexible operations. Diesel forklifts, despite lower upfront cost, are environmentally obsolete and should be phased out in favour of electrified solutions as soon as cleaner power becomes available.

6.1 Recommendations

- **Warehouse operators:** Conveyor belts should be reserved for high-throughput flows, and AGVs / electric forklifts with solar charging for flexible operations.

- **Manufacturers/importers:** Provide solar-compatible, dust-proof packaging and battery return programs.
- **Government:** Speed up grid decarbonization, slap high taxes on any new diesel forklifts, and offer incentives for electric/conveyor systems and warehouse solar installations.
- **Future research:** Extend to full life-cycle costs, social implications, and novel hydrogen/cobot technologies within 2030–2035 energy scenarios for Nigeria.

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