Converting $PM_{2.5}$ Emissions to Population Health Consequences: An Introductory Analysis of Life Cycle Impact Assessment Techniques

Joshua Onichino[†]

Presented to Dr. Sarah M. Jordaan[‡]

[†]Med-P Qualifying Year, and [‡]Department of Civil Engineering, McGill University

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Abstract—This report examines the systematic translation of $PM_{2.5}$ emissions into quantifiable implications for population health within the framework of sustainability research. Through the lens of sustainability, this study delves into the realm of Life Cycle Impact Assessment (LCIA) techniques, elaborating on the potential health consequences stemming from these emissions. The primary objective is to furnish an accessible conceptual framework for those unacquainted with this branch of sustainability research. Beginning with the identification of $PM_{2.5}$ emissions, this work traces the various stages in the process by which $PM_{2.5}$ emissions impact population health. Foundational to this analysis is the collection of emissions data, capturing the mass of $PM_{2.5}$ particles released into the environment. This marks the beginning of the process and is followed by exposure modeling, which reveals how these particles disperse and interact with human environments. The trajectory then advances towards the intersection of exposure and health outcomes, which requires an understanding of epidemiological studies—investigations that analyze patterns and causes of health and disease in populations—and concentration-response functions—functions that describe the relationship between exposure levels and health outcomes. The interplay between these components facilitates the estimation of health impacts, transforming $PM_{2.5}$ exposure into potential health consequences for populations. This report amalgamates LCIA methodologies, navigates challenges, and delineates implications inherent in the integration of LCIA techniques. These techniques serve as a quantitative lens to scrutinize population health repercussions arising from $PM_{2.5}$ emissions, designated for an academic audience in the sphere of sustainability research.

Key words—$PM_{2.5}$, LCIA, Sustainability, Population health, Emissions data, Exposure modeling, Epidemiology, Health impacts, Concentration-response, Sustainable decision-making

1. Introduction

In the context of sustainable development, the need for robust tools to dissect complex environmental interactions and provide empirical, scientific guidance to policymakers is crucial. Among these tools, Life Cycle Assessment (LCA) stands out as a fundamental methodology. It analyzes the life cycles of products, processes, and systems to quantify environmental impacts. This discussion foregrounds a vital component of LCA—Life Cycle Impact Assessment (LCIA)—to clarify its significance, distinctiveness, and implications for understanding the effects of $PM_{2.5}$ emissions on population health.

LCA is a holistic framework that can serve to assess the environmental footprint of a product or process across its life cycle, spanning from raw material extraction to end-of-life scenarios. Its value lies not only in unraveling complex environmental interactions but also in facilitating well-informed decisions by quantifying trade-offs in relation to different environmental impact categories.

Central to LCA is LCIA. The latter applies a rigorous analysis of raw data from a product's or process' different life cycle stages. This can in turn inform resource allocation, policy formulation, and product design, all with the purpose of reaching optimal sustainability outcomes. LCIA excels at synthesizing diverse environmental metrics into a cohesive scale, comprehensively analyzing potential impacts such as climate change, resource depletion, and human health effects.

LCIA distinguishes itself from other modeling frameworks through its capacity to comprehensively encompass nuances that frequently elude simplified, single-point methods. Unlike methods that focus solely on isolated factors, LCIA's scope extends to include intricate exposure pathways, health outcomes, and the broader environmental context. This inclusive approach reflects its alignment with the call for more holistic impact assessments, which recognize and analyse the interconnectedness of various factors that affect environmental impacts (Bulle et al., 2019).

A range of current scholarship draws on a multifaceted approach to assessing environmental challenges' impacts on public health burdens. This includes Bulle et al.'s global insights in IMPACT World+ (Bulle et al., 2019) and Achilleos et al.'s review of fine particulate matter effects (Achilleos et al., 2017). Further, Fantke et al.'s Basel Workshop findings highlight LCIA's diverse applications in public health and sustainability (Fantke et al., 2015).

The present report examines LCIA's methodologies, challenges, and implications, merging insights from Smith et al.'s study on "Energy and Human Health" (Smith et al., 2013) and Verones et al.'s regional damage assessment in LC-IMPACT (Verones et al., 2020). It illuminates LCIA's role in quantifying the impacts of $PM_{2.5}$ emissions on population health to allow for robust decision-making.

2. Report Writing Process

The method employed in the creation of this report involved three key phases: literature review, reference repository development, and report writing. These stages are discussed in turn in this section.

2.1. Literature Review

The first two weeks of this project focused on reviewing scholarly databases to identify and review relevant literature for this project. All pertinent sources were collected and annotated. Annotations noted the core arguments and contribution of each source, rated each source by relevance, and documented quotations and key ideas emerging within each that were especially revealing or helpful. All annotations were stored in a Google Sheets spreadsheet.

2.2. Reference Repository Development

All relevant sources collected and annotated were then stored in an EndNote library. The EndNote repository was helpful for two reasons: first, it provided a single site for retaining all sources, and second, it facilitated citation of these works during the report writing process. While not all sources collected and annotated in the repository are cited in this report, they all contributed to shaping the ideas relayed herein.

2.3. Report Writing

ChatGPT was employed routinely throughout the redaction of this report. Due to the limited literacy of the author regarding LCA-related publications, excerpts selected from publications were provided to ChatGPT so that these could be broken down and explained in simpler terms. These explanations supported the structuring of certain sections in this report, with the most notable example being 5. Methodology. Further, ChatGPT was used to determine the optimal structure for this report as well as the sections and subsections therein. This AI model was thus used as a research tool to facilitate the understanding and organization of concepts relevant to this work. Moreover, text that it generated in response to prompts given was adapted and integrated into this report so that the report directly responded to the mandate that was given.

For access to the Google Sheets spreadsheet, EndNote library, and a copy of this report, please follow this link to a Google Drive folder: https://drive.google.com/drive/folders/12N4FLx2XUe-DzOxllswZ7nXHGnKPFAi2?usp=sharing.

3. Background

This section begins by elucidating the nature of $PM_{2.5}$ emissions, their sources, and associated health effects. It proceeds by exploring various particulate matter categories, including primary and secondary particles, and considers the role of volatile organic compounds

(VOCs). This foundation sets the stage for introducing LCA and its capacity to assess and quantify the risk to human health engendered by these particles.

3.1. PM Overview

Particulate Matter (PM) consists of microscopic airborne particles consisting of solid and liquid matter. $PM_{2.5}$ refers to particles with a diameter of 2.5 micrometers or smaller, while PM_{10} refers to larger particles with a dimeter of 10 micrometers or smaller. The classification by size of PM can extend beyond these thresholds, with some researchers considering particles with sizes in between 10 and 2.5 micrometers (Humbert et al., 2011).

PM can be primary (emitted directly into the atmosphere), secondary (formed through various chemical reactions of precursors in the atmosphere due to a wide range of precursors), tertiary (formed through further reactions and transformations of secondary particles), or ultrafine (formed from primary or secondary sources which nucleate in the atmosphere to produce these nanoparticles).

3.2. $PM_{2.5}$ Emissions

$PM_{2.5}$ emissions arise from a diverse array of sources, including industrial activities, vehicular transportation, construction, and natural agents such as dust. In particular, the transportation sector has emerged as a prominent contributor to $PM_{2.5}$ emissions, releasing particles through exhaust emissions and tire wear. Vehicular emissions are a significant concern due to their substantial contribution to urban air pollution, especially in densely populated areas. The work by Cao et al. provides an. insightful analysis into the evolution of $PM_{2.5}$ measurements and standards, shedding light on the contributions of vehicular sources to particulate matter pollution (Cao et al., 2013).

3.3. $PM_{2.5}$ Health Impacts

The health impacts of $PM_{2.5}$ are profound, manifesting as a range of respiratory and cardiovascular disorders. Of particular concern is $PM_{2.5}$'s capacity to infiltrate the respiratory system and even enter the bloodstream due to its minuscule size, posing a greater health risk than coarser particles like PM_{10}. Vulnerable populations, such as children and the elderly, are especially susceptible to the adverse effects of $PM_{2.5}$ exposure.

Greene & Morris' investigation of health risks associated with $PM_{2.5}$ exposure in Washington D.C. exemplifies this point; the researchers found significant risks of pediatric emergency room visits and lifetime heightened lung cancer risks for different subpopulations studied in the D.C. area, which they correlated to $PM_{2.5}$ exposure (Greene & Morris, 2006).

The present report is not solely concerned with the health impacts of $PM_{2.5}$; it examines the methods by which they are quantified. Yet, understanding these health impacts is necessary to quantify the public health burdens due to $PM_{2.5}$ emissions. That information is, in turn, essential to inform public health policy decision-making.

3.4. Volatile Organic Compounds (VOCs)

VOCs vaporize into the atmosphere, originating from vehicles, industry, and solvents. VOCs contribute to secondary $PM_{2.5}$ formation and are associated with respiratory irritation and exacerbation of existing conditions.

3.5. Literature Overview

Research, such as Achilleos et al.'s (Achilleos et al., 2017) meta-analysis, highlights the acute effects of fine particulate matter on mortality. Heo et al. (Heo, Adams, & Gao, 2016) assess the economic impact of $PM_{2.5}$ emissions. Both studies, as well as others that have been reviewed in preparation for this report, underscore the burden on human health that is the direct result of these pollutants.

3.6. Life Cycle Assessment (LCA)

LCA serves as an indispensable tool for evaluating the comprehensive environmental impacts of products, processes, and systems throughout their life cycles. By quantifying impacts across categories such as human health and ecosystem quality, LCA provides a robust framework for informed and sustainable decision-making. The integration of LCA into the assessment of pollutants like $PM_{2.5}$ emissions facilitates a more comprehensive understanding of these emissions' implications for environmental sustainability and human health. The way in which the impacts on population health due to $PM_{2.5}$ are calculated will be explored in greater detail in 5. Methodology.

4. Life Cycle Assessment (LCA) and Health Impact Assessment (HIA)

Various methodologies are required for a comprehensive analysis of the potential health implications of $PM_{2.5}$ emissions and their intricate pathways. This section explores the synergy of HIA and LCA methods, illustrating how their integration enhances the evaluation of health consequences associated with $PM_{2.5}$ emissions. HIA and LCA are complementary and mutually nourishing approaches in this area of study. Examining the interplay between emissions and human health through the lens of HIA offers valuable insights into the potential positive and negative impacts of population health policy choices. This interdisciplinary approach, bolstered by LCA's environmental assessment framework, paves the way for a more comprehensive understanding of the environmental and health dimensions of $PM_{2.5}$ emissions.

4.1. HIA Overview

HIA is a comprehensive framework designed to assess the potential health effects of policies, projects, and programs across various sectors. The primary purpose of HIA is to identify and evaluate the potential positive and negative health impacts of policy decisions, offering insights to policymakers, planners, and stakeholders. HIA enhances decision-making processes by integrating health considerations, ultimately promoting well-informed policies that prioritize public health and well-being (Harris-Roxas & Harris, 2011).

4.2. The Intersection of LCA and HIA

LCA and HIA intersect through their shared objective of evaluating the implications of various actions on human health and the environment. While LCA focuses on assessing the environmental impacts of products and processes throughout their life cycle, HIA emphasizes the potential health consequences of decisions. This alignment makes LCA and HIA valuable companions in the pursuit of sustainable development, as they provide a comprehensive and integrated understanding of both environmental and health dimensions.

4.3. Utilizing HIA Data and Methodologies in LCA for $PM_{2.5}$ Emissions

LCA specialists leverage data and methodologies from HIA to estimate the health consequences associated with $PM_{2.5}$ emissions. HIA provides valuable insights into the pathways through which $PM_{2.5}$ exposure affects human health, offering quantitative data on the potential magnitude of health outcomes. By integrating HIA-derived information into LCA models, specialists can refine the assessment of health-related impacts caused by $PM_{2.5}$ emissions across the entire life cycle of products or processes.

The integration of HIA data allows LCA practitioners to account for a wider spectrum of health effects, ranging from acute respiratory and cardiovascular issues to long-term chronic diseases. This comprehensive approach ensures that the evaluation of health impacts stemming from $PM_{2.5}$ emissions remains robust and nuanced.

Khreis et al. draw on both HIA and LCA to assess the health impacts of urban transportation systems, providing insights into how these methodologies collaboratively enhance the understanding of health-related consequences of environmental decisions (Khreis et al., 2017). This approach aligns with the holistic assessment ethos of LCA while acknowledging the significance of health considerations in the decision-making process.

5. Methodology

A rigorous methodology is needed to study LCA given the range of factors to be accounted for in the conversion of $PM_{2.5}$ emissions into population health consequences. This section expounds upon the various stages of this conversion process, elucidating the complexities involved in quantifying the environmental and health dimensions of $PM_{2.5}$ emissions. The integration of diverse factors and methodologies ensures a fulsome understanding of the potential health impacts arising from $PM_{2.5}$ exposure.

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5.1. Data Collection for $PM_{2.5}$ Emissions

The assessment of population health consequences attributed to $PM_{2.5}$ emissions begins with the meticulous collection of data that captures the complex characteristics of emitted particles. Data relate to multiple factors, each of which contributes to the overall understanding of the composition and behavior of $PM_{2.5}$ emissions.

5.1.1. Composition of Emitted Particles

To comprehensively characterize $PM_{2.5}$ emissions, it is imperative to understand the composition of these particles. This involves identifying the chemical constituents present in emissions, which can encompass a wide spectrum of elements, compounds, and pollutants. Analytical techniques such as mass spectrometry, elemental analysis, and spectroscopy play a pivotal role in identifying and quantifying these constituents. Studies such as those conducted by Almeida et al. showcase the application of these techniques to unveil the complex composition of emitted particles (Almeida et al., 2005).

5.1.2. Particle Size Distribution

The size distribution of emitted particles is a key determinant of their behavior in the atmosphere and their potential health impacts. Particles of varying sizes can penetrate different regions of the respiratory tract, influencing their potential to cause health issues. Measurement techniques like cascade impactors and optical particle counters are employed to establish the size distribution profile. Landrigan et al. employ these techniques to analyze the particle size distribution of $PM_{2.5}$ emissions from different sources, shedding light on the variability in particle sizes across emission types (Landrigan et al., 2018).

5.1.3. Stack Height and Dispersion

The height at which emissions are released from stacks significantly influences their dispersion and potential exposure levels. The plume from a stack can disperse over a larger area at higher altitudes, impacting the extent of exposure. Dispersion models, informed by factors such as stack height and meteorological conditions, are utilized to estimate the spatial spread of emissions. Examples such as the study by Lateb et al. demonstrate the significance of considering stack height in dispersion modeling (Lateb et al., 2011).

5.1.4. Primary PM Emissions and Precursors

Quantifying both primary emissions and precursor levels is essential for understanding the contributions of different emission sources to overall $PM_{2.5}$ levels. Work by Guo et al. highlights the importance of primary emissions and precursors in assessing $PM_{2.5}$ concentrations (Guo et al., 2017).

5.1.5. Optimizing Detector Placement

When collecting data, the spatial distribution of detectors for measuring $PM_{2.5}$ emissions becomes a crucial consideration. Achieving accurate coverage while optimizing detector placement to balance cost-efficiency is a challenge. Studies like Guo et al.'s on optimizing monitoring networks exemplify an effort to strategically position detectors so as to capture spatial variability in $PM_{2.5}$ levels while minimizing cost (Guo et al., 2018).

In summary, the collection of data for $PM_{2.5}$ emissions entails a multifaceted process that involves comprehensive analyses of particle composition, size distribution, stack height, primary emissions, and precursor concentrations. Employing techniques such as mass spectrometry, cascade impactors, and dispersion modeling, researchers endeavor to create a holistic profile of emitted particles. Furthermore, strategic placement of detectors optimizes spatial coverage, enabling researchers to gain insights into the complex nature of $PM_{2.5}$ emissions and their potential health implications.

5.2. Fate

The behavior of $PM_{2.5}$ emissions after their release into the atmosphere is a vital component of assessing exposure and consequential health effects. The concept of fate, often measured in years, quantifies the temporal duration $PM_{2.5}$ remains in the air. Factors such as wind speed, meteorological conditions, mixing height (that is, the height above ground level at which a pollutant can be disbursed), and interactions between primary and secondary PM play a critical role in determining the dispersion and atmospheric presence of $PM_{2.5}$. The relationship between these factors contributes to calculating the mass of $PM_{2.5}$ in ambient air, a pivotal parameter for gauging exposure.

5.3. Measuring Mass in Ambient Air

Understanding the mass of $PM_{2.5}$ in ambient air requires a combination of measurement techniques and mathematical modeling. These approaches collectively provide insights into the concentration of $PM_{2.5}$, which is necessary for assessing exposure levels and potential health impacts.

5.3.1. Gravimetric Sampling

Gravimetric sampling involves the collection of airborne particles on a filter substrate, followed by precise weighing to determine the mass of $PM_{2.5}$. This technique provides direct measurements of particle mass concentration and is often used as a reference method. Researchers deploy high-volume samplers equipped with filters to capture particles from the air. Post-collection, the filters are conditioned to stabilize their weight, and subsequent weighing yields the mass of $PM_{2.5}$. Studies such as those by Zhu et al. exemplify the application of gravimetric sampling to assess $PM_{2.5}$ mass concentrations while comparing this technique to real-time sampling (Zhu et al., 2011).

5.3.2. Optical Methods

Optical methods utilize the light-scattering or light-absorption properties of particles to estimate $PM_{2.5}$ concentrations. These methods are efficient and allow for continuous monitoring. Devices such as nephelometers and photometers quantify the scattering or absorption of light by particles suspended in the air. By calibrating the measurements, researchers can infer $PM_{2.5}$ mass concentrations. A study by Petzold et al. underscores the accuracy and applicability of optical methods for assessing aerosol mass concentrations (Petzold et al., 2013).

5.3.3. Chemical Analysis

Chemical analysis involves determining the elemental or chemical composition of particles in ambient air to indirectly estimate $PM_{2.5}$ mass concentrations. X-ray fluorescence (XRF), X-ray diffraction (XRD), and ion chromatography are among the techniques used to identify and quantify specific elements or compounds present in the particles. Researchers can then use these measurements to calculate $PM_{2.5}$ mass concentrations based on established relationships between chemical constituents and mass. Work by Favez et al. demonstrates the use of chemical analysis to estimate $PM_{2.5}$ mass concentrations in urban environments (Favez et al., 2009).

By integrating data from these measurement techniques, researchers gain a comprehensive understanding of $PM_{2.5}$ mass concentrations in ambient air. This insight into the presence of $PM_{2.5}$ is indispensable for quantifying exposure and further assessing the potential health implications of these emissions.

5.4. Exposure Assessment

Exposure assessment involves evaluating the amount of $PM_{2.5}$ that residents in a specific area are subjected to over the course of a year. It considers factors such as wind speed, meteorological conditions, mixing height, and the interplay between primary and secondary PM. Population density, composition, and particle size distribution further influence the extent of exposure. By analyzing these parameters, LCA practitioners can determine the level of exposure, forming a crucial link between emitted $PM_{2.5}$ and its potential health implications.

5.5. Intake Fraction

The intake fraction is a critical metric in the assessment of population health consequences attributed to $PM_{2.5}$ emissions. It serves as a bridge between exposure and subsequent health impacts, shedding light on how much of the exposed $PM_{2.5}$ is taken up by the human body within a given population and area. This assessment delves into a range of variables, including exposure levels, population density, particle composition, and particle size distribution.

Calculating the intake fraction requires a comprehensive consideration of the above variables to quantify the proportion of inhaled $PM_{2.5}$ that eventually enters the human body. To illustrate, a study by Humbert et al. in 2011 explores the methodology for calculating intake fraction, providing insights into the mathematical framework and considerations involved (Humbert et al., 2011). It recommends approaches for LCA assessment, offering a robust foundation for estimating intake fractions tailored to specific scenarios.

By integrating these factors, researchers can arrive at an intake fraction value that accounts for variations in exposure and population characteristics. This parameter plays a pivotal role in the subsequent calculation of categorization factors—a key facet of the conversion process within LCA.

5.6. Effect Factors

Effect factors also are central to the process of converting $PM_{2.5}$ emissions into population health consequences. They are grouped below into three subsections: dose-response relationship, multiple endpoints and subpopulation sensitivity, and measuring severity with Disability-Adjusted Life Years (DALYs).

5.6.1. Dose-Response Relationship

The dose-response relationship refers to the correlation between the amount of a given substance ingested and a particular response. The assessment of the dose-response relationship hinges on understanding how changes in $PM_{2.5}$ exposure levels influence the incidence of disease. Concentration-response functions, derived from epidemiological studies, play a pivotal role in quantifying this relationship. By analyzing large datasets of health outcomes and corresponding $PM_{2.5}$ exposures, researchers establish the link between exposure levels and the likelihood of specific health effects.

5.6.2. Multiple Endpoints and Subpopulation Sensitivity

Different diseases or health effects may manifest, or yield given endpoints, due to $PM_{2.5}$ exposure, and these effects can vary in severity. Additionally, subpopulations within a larger demographic may exhibit varying sensitivities to $PM_{2.5}$ exposure. For instance, individuals with preexisting health conditions may be more susceptible to adverse effects. Considering these factors renders the predictions as to health outcomes more sensitive.

5.6.3. Measuring Severity with Disability-Adjusted Life Years (DALYs)

To capture the full spectrum of health impacts, severity is quantified using DALYs per case. DALYs integrate both morbidity and mortality, providing a holistic measure of the overall impact of a specific health effect. This metric is calculated by considering not only the years of life lost due to premature mortality but also years lived with disability resulting from the health condition.

The calculation of DALYs involves several steps. First, researchers identify the health outcomes associated with $PM_{2.5}$ exposure and estimate the number of cases of these health outcomes within a specific population. The years of life lost due to premature mortality are determined by subtracting the age at which a person dies from the standard life expectancy. For example, if a person dies prematurely at the age of 60 but the standard life expectancy is 80, the years of life lost would be 20.

Additionally, DALYs account for years lived with disability, acknowledging that some health conditions not only result in premature death but also lead to reduced quality of life due to disability. Researchers also assign each health outcome associated with a disability a different weight, which are known as "disability weights". Weights are ascribed according to the severity of an outcome and the extent to which it affects a person's overall well-being. For example, a person with COVID-19 might have an outcome of having flu-like symptoms while another might require medical intervention to support respiration. In the former case, the disability weight will be lower than in the latter case. The number of years lived with disability is then multiplied by the disability weight to quantify the impact of disability on overall health.

Finally, the years of life lost and years lived with disability are summed to calculate the total DALYs for a specific health outcome. This composite metric provides a comprehensive measure of the burden of disease, accounting for both the immediate impact of premature mortality and the long-term impact of living with a disability.

The application of DALYs in the assessment of $PM_{2.5}$-related health impacts allows researchers to compare different health outcomes on a standardized scale. This facilitates the prioritization of interventions and policy decisions by quantifying the overall health burden associated with specific diseases. Work by Murray & Lopez presents a seminal framework for calculating

DALYs and offers insights into its application in assessing population health (Murray & Lopez, 1996) Incorporating DALYs into the categorization factors enables a more nuanced understanding of the severity of health impacts stemming from $PM_{2.5}$ emissions. By considering both premature mortality and years lived with disability, this metric contributes to a robust evaluation of the overall health consequences within the context of LCA.

5.7. Categorization Factors

Categorization factors serve as a bridge between the intake fraction and effect factors, enriching the assessment by accounting for diverse characteristics of different population groups.

5.7.1. Tailoring Assessments to Demographics

Categorization factors stratify populations based on demographic characteristics such as age and gender. The approach acknowledges that individuals within a population may exhibit varying sensitivities to $PM_{2.5}$ exposure, resulting in diverse health outcomes. By tailoring assessments to demographics, researchers can capture the unique vulnerabilities and susceptibilities of specific subgroups.

5.7.2. Refining Health Impact Estimations

The categorization of populations enables researchers to refine their estimations of health impacts associated with $PM_{2.5}$ emissions. Individuals within different demographic groups may experience varying degrees of exposure and physiological responses to the same levels of $PM_{2.5}$. For example, elderly individuals and children could be more susceptible to the adverse effects of $PM_{2.5}$ due to their physiological characteristics. By accounting for these variations, the assessment becomes more comprehensive, accurate, and representative of real-world scenarios.

5.7.3. Quantifying Health Consequences

Quantifying the health consequences of $PM_{2.5}$ emissions across different population groups involves the integration of categorization factors with intake fraction and effect factors. This multifaceted approach allows researchers to generate impact metrics that reflect variability of the health risks posed by $PM_{2.5}$ emissions. These metrics could include indicators such as DALYs or years of life lost due to premature mortality and morbidity.

In addition to the use of DALYs, researchers exploring the quantification of health consequences attributed to $PM_{2.5}$ emissions within the context of LCA may consider alternative metrics. While DALYs offer a comprehensive measure that integrates both premature mortality and years lived with disability, other impact metrics have also been examined.

Among these alternatives, metrics such as Quality-Adjusted Life Years (QALYs), which consider the quality of life experienced during years of healthy life, have gained attention. Additionally, measures such as the Number Needed to Harm (NNH), which indicates how many individuals need to be exposed to a risk for one additional person to experience a harmful outcome, are being explored.

The most common and accepted approach within the LCA community, however, remains the application of DALYs due to its integrated approach and established framework. However, ongoing research and discussions are shaping the exploration of diverse metrics to refine the quantification of health impacts, ensuring a comprehensive evaluation of the effects of $PM_{2.5}$ emissions on population health.

5.7.4. Revealing Differential Impacts

The incorporation of categorization factors into the conversion process within LCA reveals the nuanced and differential impacts of $PM_{2.5}$ emissions on distinct population groups. This analytical approach unveils disparities in health risks and vulnerabilities, highlighting where interventions and mitigation strategies may be most urgently needed. By quantifying the health consequences in a granular manner, researchers contribute to evidence-based decision-making and policy formulation aimed at safeguarding public health across diverse demographics.

In summary, categorization factors enhance the precision and relevance of assessing population health consequences attributed to $PM_{2.5}$ emissions. By tailoring assessments to demographics, refining health impact estimations, quantifying health consequences, and revealing differential impacts, researchers gain a deeper understanding of the complex interplay between $PM_{2.5}$ exposure and human health across diverse population groups. This comprehensive approach underscores the importance of addressing the unique susceptibilities and vulnerabilities of different demographics in the pursuit of informed and equitable policy decisions.

5.8. Calculation of Impact

The culmination of the conversion process within LCA lies in the calculation of impact. Integrating the effect factors—obtained through thorough assessments of dose-response relationships and disease incidence—results in the estimation of health consequences. The comprehensive evaluation of the implications of $PM_{2.5}$ emissions on population health emerges from this integration, providing a nuanced understanding of the potential health risks.

The methodologies outlined above constitute a meticulously structured approach to convert $PM_{2.5}$ emissions into population health consequences within the context of LCA. The seamless integration of data collection, exposure assessment, intake fraction, effect factors, categorization factors, and subsequent calculations ensures a rigorous and accurate evaluation of the environmental and health dimensions of $PM_{2.5}$ emissions.

Work by Fann et al. serves as an example of the application of these methodologies, where the authors quantified the health impacts of $PM_{2.5}$ emissions from the transportation sector using comprehensive exposure and risk assessment approaches (Fann, Baker, & Fulcher, 2012). This research showcases the efficacy of this conversion process and underscores its significance in informing policy decisions for public health and sustainable development.

In summary, the detailed methodology presented in this section empowers researchers and practitioners to navigate the complex process of converting $PM_{2.5}$ emissions into population health consequences using LCA techniques. This approach, underpinned by rigorous data collection and multidimensional assessments, paves the way for high-quality decision-making that mitigates the negative impacts of $PM_{2.5}$ emissions on both the environment and public health.

6. Case Study: Assessing Population Health Impacts of $PM_{2.5}$ Emissions

To provide a tangible illustration of the methodology presented in the previous sections, a hypothetical case study is presented in this section that demonstrates the application of the framework to a real-world scenario. This case study serves as a practical example to highlight how the steps outlined in the methodology can be employed to assess the population health consequences of $PM_{2.5}$ emissions.

6.1. Scenario Overview

Imagine a metropolitan area characterized by diverse emission sources, including industrial activities, vehicular traffic, and residential heating. With this setting in mind, we turn now to evaluating the potential health impacts of $PM_{2.5}$ emissions originating from these sources on the local population. By applying the comprehensive methodology detailed in earlier sections, the goal shall be to quantify the environmental and health dimensions of these emissions.

6.2. Data Collection and Composition Analysis

The initial step involves the meticulous collection of data regarding the emitted particles. Advanced analytical techniques, such as mass spectrometry and elemental analysis, are employed to identify the chemical constituents of the particles. This information forms the foundation for understanding the composition of $PM_{2.5}$ emissions from various sources.

6.3. Exposure Assessment

Next, the exposure of the studied population to $PM_{2.5}$ must be assessed, considering meteorological conditions, wind speed, and mixing height. By analyzing these parameters, it is possible to estimate the dispersion patterns of $PM_{2.5}$ emissions across the urban area, identifying regions with higher exposure levels. Population density and demographic data are integrated to create exposure profiles for different segments of the population.

6.4. Intake Fraction Calculation

Building upon exposure assessments, intake fractions are calculated for different demographic groups. These fractions represent the estimated proportion of inhaled $PM_{2.5}$ that enters the human body. Through the incorporation of variables such as particle composition and size distribution, the differential intake fractions for children, adults, and the elderly within the studied area are determined.

6.5. Categorization Factors and Effect Factors

Categorization factors are introduced to tailor health impact assessments to specific demographics. Susceptibility variations among age groups and genders are accounted for, enabling refined estimations of health impacts. The estimation of effect factors involves analyzing dose-response relationships using epidemiological data, yielding correlations between $PM_{2.5}$ exposure and health outcomes for different population segments.

6.6. Quantifying Health Consequences

The culmination of intake fraction, categorization factors, and effect factors leads to the quantification of health consequences. Metrics such as DALYs and years of life lost are calculated for different demographic groups, providing insights into the overall health burden posed by $PM_{2.5}$ emissions.

6.7. Insights and Policy Implications

The case study's results reveal disparities in health impacts among population segments. Vulnerabilities within specific demographic groups are highlighted, emphasizing the importance of targeted interventions. By quantifying health consequences, policy decision-makers gain evidence-based insights for formulating regulatory interventions aimed at mitigating the negative effects of $PM_{2.5}$ emissions on public health.

7. Challenges and Limitations

Converting $PM_{2.5}$ emissions into population health consequences within the context of LCA is a multifaceted endeavor that brings to light valuable insights into the environmental and health dimensions of particulate matter. However, this process is not devoid of challenges and limitations, many of which stem from the interplay between exposure, health impacts, and LCA methodologies. Acknowledging and addressing these challenges is essential for ensuring the robustness and reliability of the methodology.

7.1. Data Uncertainties and Assumptions: Navigating the LCA Context

LCA, as a holistic methodology, requires data that span various stages of a product's or process' life cycle. In the context of converting $PM_{2.5}$ emissions to health impacts, data uncertainties can pose significant challenges. Gathering accurate data on emission sources, particle behavior, and health outcomes is paramount, as these data points underpin the LCA analysis. Uncertainties in data can propagate through LCA modeling, leading to potentially biased results. Addressing data limitations and making appropriate assumptions within the LCA framework thus are crucial to the validity of the findings (Xing et al., 2016).

7.2. Exposure Variability and LCA Considerations

LCA accounts for the variability in exposure by assessing the potential impacts across the life cycle of a product or process. However, accurately quantifying exposure to $PM_{2.5}$ emissions, especially considering diversity of population groups and geographical contexts, is complex. Meteorological conditions, human behavior, and geographical features introduce variability that interacts with LCA methodologies. Bridging the gap between LCA's holistic approach and the localized nature of $PM_{2.5}$ exposure is a challenge that necessitates refining exposure modeling techniques (Sorek-Hamer, Chatfield, & Liu, 2020).

7.3. Biological Variability and LCA's Holistic View

LCA encompasses a holistic view of environmental impacts, but it must also contend with the complexities of human biology and variability. While LCA strives to generalize the relationship between $PM_{2.5}$ exposure and health impacts, the biological variability among individuals introduces nuances that are challenging to capture within the LCA framework. This challenge underscores the need to integrate biological variability into LCA health impact assessments to achieve a more realistic representation of real-world health implications (Almstrand et al., 2009; Krewski et al., 2009).

7.4. Challenges in Incorporating Long-Term Impacts

LCA inherently captures the long-term impacts of emissions, which aligns with the objective of assessing chronic health effects due to $PM_{2.5}$ exposure. However, the availability of long-term data remains limited. LCA relies on long-term health outcome data to assess chronic effects, yet such data may not always be available or comprehensive. The challenge lies in bridging the temporal scope of LCA with temporal gaps in available health data, requiring innovative approaches to extend the insights gained from short-term data (Ostro et al., 2009; Pope III et al., 2004).

7.5. Causality and LCA's Systems Perspective

Attributing specific health outcomes to $PM_{2.5}$ emissions involves establishing causal relationships within a complex system. LCA's systems perspective aligns with this endeavor, but also highlights the intricacies of isolating the contribution of $PM_{2.5}$ emissions amid the myriad factors influencing health. The challenge lies in navigating the causal web within LCA's systems approach while acknowledging the limitations in establishing direct causality between emissions and specific health effects (Cohen et al., 2017; Lelieveld et al., 2015).

7.6. Forging Ahead: Future Research within the LCA Framework

While challenges persist, the application of LCA methodologies to assess $PM_{2.5}$-related health impacts presents promising opportunities for future research.

7.6.1. Advancing LCA Data

Efforts to enhance the accuracy and availability of LCA data, particularly pertaining to emissions, exposure pathways, and health outcomes, can significantly reduce uncertainties and biases (Brunekreef & Holgate, 2002; Dockery et al., 1993).

7.6.2. Integrating LCA and Exposure Modeling

Integrating advanced exposure modeling techniques with LCA methodologies can provide a more refined understanding of the localized impacts of $PM_{2.5}$ emissions (Jerrett et al., 2009; Kloog et al., 2012).

7.6.3. Holistic Health Impact Assessments

Enhancing LCA health impact assessments by incorporating individual susceptibility, genetic factors, and real-world health data can enrich the methodology's capacity to capture variability (Kloog et al., 2015).

7.6.4. Cross-Disciplinary Collaboration

Collaborations between experts in environmental science, public health, and LCA can foster cross-disciplinary innovations, ultimately leading to more comprehensive and accurate health impact assessments (Perera et al., 2008; Samet et al., 2000).

7.7. Inherent Limitations and Continued Reflection

It is important to acknowledge that even with advancements in methodology, certain limitations will remain inherent. The complexity of human health, the dynamic nature of environmental interactions, and the inherent uncertainties in data and related assumptions underscore the need for continuous reflection on and review of the results generated by this methodology.

In summary, the conversion of $PM_{2.5}$ emissions into health impacts through the lens of LCA offers invaluable insights into the complex interplay between environmental pollutants and public health. While challenges abound, addressing these obstacles within the context of LCA enhances the contributions and relevance of this approach, fostering informed decision-making and facilitating the pursuit of healthier and more sustainable futures.

8. Implications for Sustainable Decision-Making

LCA techniques yield potential insights that extend beyond the boundaries of scientific understanding. As indicated, they promise more informed policy choices that ameliorate environmental sustainability and public health. Notably, by elucidating the relationship between particulate matter exposure and health impacts, LCA equips policymakers and stakeholders with valuable tools to prioritize interventions, formulate policies, and promote sustainable development.

8.1. Prioritizing Interventions

The insights garnered from the conversion of $PM_{2.5}$ emissions into health impacts serve as a compass guiding the prioritization of interventions to address the adverse effects of particulate matter. By quantifying the magnitude of health risks associated with different emission sources and pathways, policymakers can discern which sources contribute most significantly to health impacts and thereby make strategic choices about how to invest limited resources for intervention. For instance, if the analysis reveals that a specific sector's emissions pose disproportionate health risks to vulnerable populations, policymakers are well-advised to concentrate their attention and energy on that sector. This in turn has benefits from a common good perspective, building public confidence in government decision-making that is both evidence-based and effective in its results vis-à-vis improved health outcomes (Hänninen et al., 2014).

8.2. Formulating Targeted Policies

The integration of LCA methodologies with health impact assessments offers a data-driven foundation for policy formulation. Policymakers armed with knowledge about the health consequences of $PM_{2.5}$ emissions can tailor policies to address specific emission sources and exposure pathways. For instance, if the analysis demonstrates that vehicular emissions are a major contributor to health impacts in urban areas, policymakers can enact policies that incentivize cleaner transportation technologies and promote public transit. Moreover, policies can be designed to target specific demographic groups that exhibit greater susceptibility to health effects, ensuring equitable protection across populations (Pope III et al., 2002).

8.3. Supporting Sustainable Development Goals

The implications of this analysis align with global sustainable development goals. By quantifying the health impacts of $PM_{2.5}$ emissions, stakeholders can contribute to United Nations (UN) Goal 3: "Good Health and Well-Being," by fostering initiatives that reduce the burden of disease attributed to environmental pollutants. Additionally, insights generated further UN Goal 11: "Sustainable Cities and Communities," by guiding urban planning and policy implementation that improves air quality and enhances residents' quality of life. Through the actionable information provided by this analysis, stakeholders can contribute to multiple dimensions of sustainable development, ensuring a harmonious balance between human well-being and environmental stewardship (United Nations, 2021).

8.4. Engaging Stakeholders

The transparent and data-driven nature of LCA-based health impact assessments encourages meaningful stakeholder engagement. Policymakers, community leaders, industry representatives, and advocacy groups can participate in discussions based on evidence rather than conjecture or ideology. This fosters collaborative, rational decision-making that aligns diverse perspectives with common goals. Stakeholder engagement enhances the implementation of policies, as interventions are more likely to be embraced by the public when they are supported by well-substantiated findings and inclusive dialogues (Maibach et al., 2015).

8.5. Monitoring and Adaptation

The ongoing monitoring of $PM_{2.5}$ emissions and their health impacts is an inherent component of the sustainable decision-making process. LCA-based assessments provide a baseline against which the effectiveness of interventions and policies can be evaluated. Regular updates to the analysis allow for the tracking of progress and the identification of emerging trends. If new sources of $PM_{2.5}$ emissions are identified, or if exposure patterns change, stakeholders can adapt policies to address these evolving realities. LCA's dynamic nature ensures that decision-making remains responsive to changing environmental, societal, and technological landscapes (European Environment Agency, 2020).

9. Conclusions

Incorporating health considerations into sustainability research through the lens of LCA offers profound insights into the multifaceted relationship between

$PM_{2.5}$ emissions and population health impacts. This analysis, driven by robust data and methodologies, unveils challenges in exposure assessment, data uncertainties, and the complexities of biological variability. By quantifying health risks, this approach equips decision-makers to prioritize interventions, formulate targeted policies, and advance sustainable development goals. Stakeholder engagement, dynamic monitoring, and cross-disciplinary collaboration emerge as catalysts for impactful change. In bridging scientific understanding with actionable strategies, this methodology harmonizes public health and environmental stewardship, thereby fostering a resilient future.

10. References

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