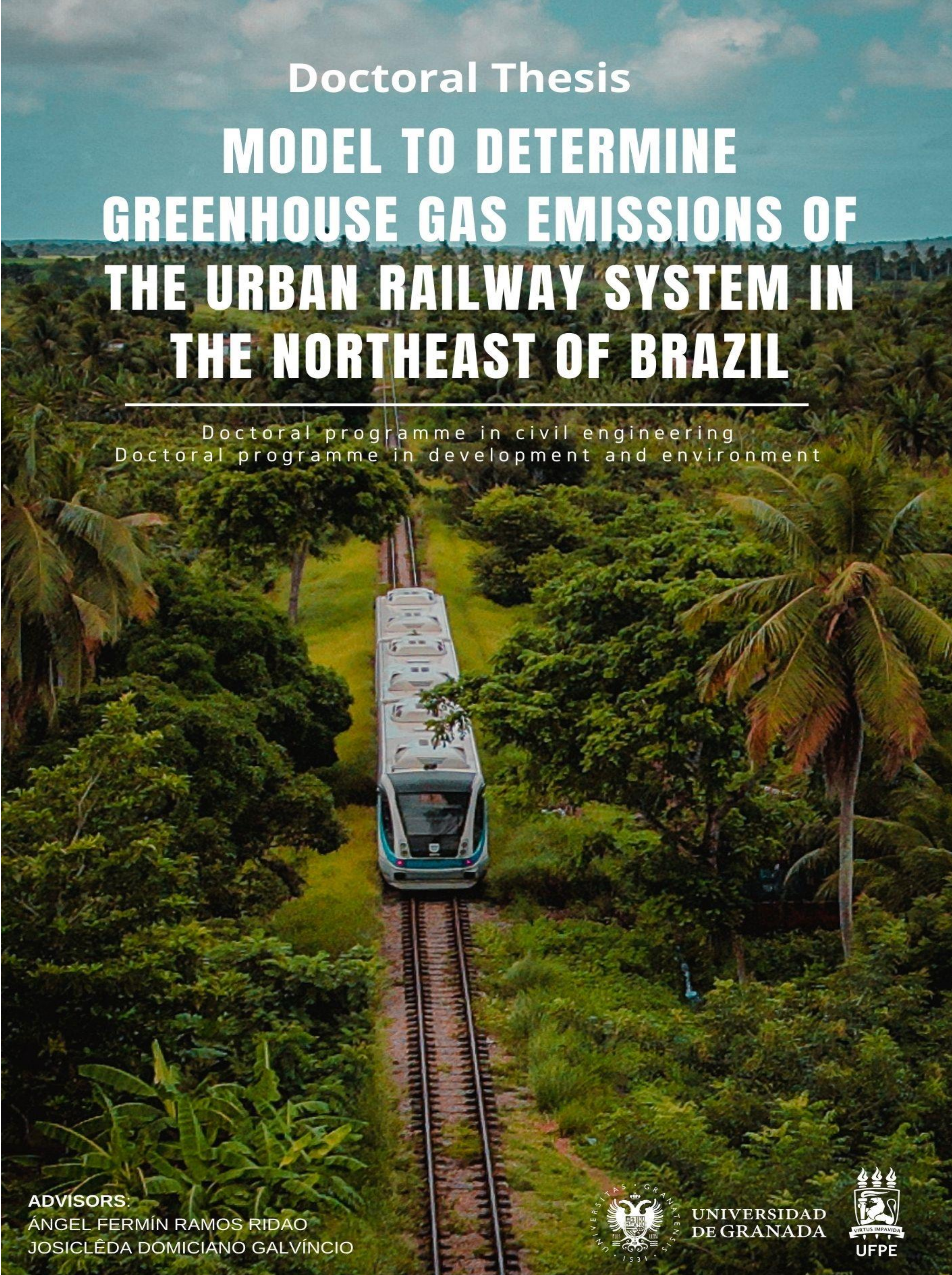

Doctoral Thesis

MODEL TO DETERMINE GREENHOUSE GAS EMISSIONS OF THE URBAN RAILWAY SYSTEM IN THE NORTHEAST OF BRAZIL

Doctoral programme in civil engineering
Doctoral programme in development and environment

ADVISORS:
ÁNGEL FERMÍN RAMOS RIDAO
JOSICLÊDA DOMICIANO GALVÍNCIO

UNIVERSIDAD DE GRANADA
UFPE

DIOGO DA FONSECA SOARES

MODEL TO DETERMINE GREENHOUSE GAS EMISSIONS OF THE URBAN RAILWAY SYSTEM IN THE NORTHEAST OF BRAZIL

MODELO PARA DETERMINAR LAS EMISIONES DE GASES DE EFECTO INVERNADERO INVERNADERO DEL SISTEMA FERROVIARIO URBANO EN EL NORESTE DE BRASIL

MODELO PARA DETERMINAR EMISSÕES DE GASES DE EFEITO ESTUFA DO SISTEMA FERROVIÁRIO URBANO NO NORDESTE DO BRASIL

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DOCTORAL PROGRAMME IN CIVIL ENGINEERING AT THE UNIVERSITY OF GRANADA, SPAIN AND DOCTORAL PROGRAMME IN DEVELOPMENT AND ENVIRONMENT AT THE FEDERAL UNIVERSITY OF PERNAMBUCO, BRAZIL

2023

Editor: Universidad de Granada. Tesis Doctorales
Autor: Diogo Da Fonseca soares
ISBN: 978-84-1195-101-2
URI: https://hdl.handle.net/10481/85730

Study presented by Diogo da Fonseca Soares to obtain the degree of Doctor from the University of Granada. Dissertation carried out under the guidance of Dr. Ángel Fermín Ramos Ridao, Associate Professor of the Department of Civil Engineering at the University of Granada, and Dr. Josicleda Domiciano Galvinicio, Associate Professor of the Department of Geographic Sciences at the Federal University of Pernambuco.

The doctoral candidate, Diogo da Fonseca Soares, and the thesis supervisors, Ángel Fermín Ramos Ridao and Josicleda Domiciano Galvinicio, hereby declare that, by signing this doctoral thesis, the work has been completed by the doctoral candidate under the guidance of the thesis supervisors, and to the best of our knowledge, the rights of other authors to be cited have been respected when their results or publications have been used.

Fdo. Ángel Fermín Ramos Ridao

Fdo. Josicleda Domiciano Galvinicio

THESIS AS A GROUP OF PUBLICATIONS

The present doctoral thesis is presented as a compilation of research works published by the doctoral candidate in relevant scientific media within their field of expertise. The following requirements have been met:

I. A report from the thesis advisors has been submitted regarding the suitability of presenting the thesis in this format.

II. The co-authors of the works have provided written acceptance for their inclusion as part of the doctoral thesis.

III. The articles comprising the doctoral thesis have been published or accepted after the completion of the bachelor's and master's degrees, and they have not been used in any previous thesis. Mention is made of the University of Granada through the affiliation of the doctoral candidate.

LIST OF PUBLICATIONS

Diogo Da Fonseca Soares, Josicleda Domiciano Galvinicio, Sayonara Eliziario, Angel Fermin Ramos-Ridao A Bibliometric Analysis of the Trends and Characteristics of Railway Research. October 2022. DOI https://doi.org/10.3390/su142113956

- Journal: Sustainability
- Impact Factor 2022: 3,9 / Cuartil Q2 / Ranking Categoria Environmental Sciences 114/274 / Brazil Qualis Capes A2 (Environmental Sciences / Engineering Multidisciplinary)
- Received: 28 September 2022 / Revised: 14 October 2022 / Accepted: 24 October 2022 / Published: 27 October 2022

Diogo Da Fonseca Soares, Mariko Carneiro, Lucian Hendyo Max, Angel Fermin Ramos-Ridao An Approach for Water and Energy Savings in Public Buildings: A Case Study of Brazilian Rail Company. DOI https://doi.org/ 10.3390/su142315921

- Journal: Sustainability
- Impact Factor 2022: 3,9 / Cuartil Q2 / Ranking Categoria Environmental Sciences 114/274 / Brazil Qualis Capes A2 (Environmental Sciences / Engineering Multidisciplinary)
- Received: 1 November 2022 / Revised: 23 November 2022 / Accepted: 24 November 2022 / Published: 29 November 2022

Diogo Da Fonseca Soares, Sayonara Eliziario, Josicleda Domiciano Galvinicio, Angel Fermin Ramos-Ridao. Life-Cycle Greenhouse Gas (GHG) Emissions Calculation for Urban Rail Transit Systems: The Case of Pernambuco Metro. August 2023. DOI https://doi.org/10.3390/app13158965

- Journal: Applied Sciences
- Impact Factor 2022: 2,7 / Cuartil Q1 / Ranking Categoria Q1 (General Engineering) 42/90 / Brazil Qualis Capes A3 (Environmental Sciences/ Engineering/ Multidisciplinary)
- Received: 4 July 2023 / Revised: 30 July 2023 / Accepted: 3 August 2023 / Published: 4 August 2023

Diogo Da Fonseca Soares, Sayonara Eliziario, Josicleda Domiciano Galvinicio, Angel Fermin Ramos-Ridao. A tool of life-cycle assessment to determine greenhouse gas emissions of the urban railway system in the northeast of brazil.

- Journal: Transportation Research Part D: Transport and Environment
  Impact Factor 2022: 7.6 / Cuartil Q1 / Ranking Categoria Transportation Sciemce 8/40
  Brazil Qualis Capes A1 (Environmental Sciences / Engineering / Multidisciplinary)
- Sent: 27 August 2023

Diogo Da Fonseca Soares, Sayonara Eliziario, Josicleda Domiciano Galvinicio, Angel Fermin Ramos-Ridao. Life Cycle Assessment on Greenhouse Gas Emissions in Railways: State of the Art Analysis and Systematic Review of Research Progress

- Journal: Journal of Cleaner Production
  Impact Factor 2022: 11.1 / Cuartil Q1 / Ranking Categoria Engineering, Environmental 8/55
  Brazil Qualis Capes A1 (Environmental Sciences / Engineering / Multidisciplinary)
- Sent: 27 August 2023

AGRADECIMIENTOS

Quisiera expresar mi sincera gratitud a todas las personas que desempeñaron un papel fundamental en el camino que culminó en la conclusión de esta tesis. Este trabajo no solo refleja mi esfuerzo, sino también el invaluable apoyo y las generosas orientaciones de muchas personas destacadas.

En primer lugar, a mis queridos padres, les agradezco de todo corazón por guiarme desde mi infancia con la sabia lección de que la educación es el cimiento del éxito. Sus palabras han resonado a lo largo de los años y me han motivado a perseverar, recordándome que el conocimiento es el poder que nos lleva más allá de nuestros límites. Sin su amor y aliento, no habría llegado tan lejos.

A mi incansable compañero en todo momento, Rafael Cámara Norat, mi gratitud es profunda y duradera. Su apoyo constante y su confianza en mis ideas, incluso cuando parecían audaces al principio, fueron la fuerza que me impulsó. Estuviste a mi lado, comprendiendo mi potencial y alentándome a seguir adelante. Tu habilidad para elevar mi autoestima y brindar apoyo emocional hizo toda la diferencia en mi trayectoria, permitiéndome superar desafíos y lograr conquistas que jamás imaginé.

A mi orientador en España, Ángel Firmin Ramos Ridao, le agradezco inmensamente por su orientación transformadora. Su cálida acogida en su país y la oportunidad de aprender y crecer en Andalucía, especialmente en Granada, son recuerdos que guardaré para siempre en mi corazón. Ángel, tu orientación no solo abarcó el aspecto académico, sino también cómo investigar y convertirse en un profesional comprometido en el área de educación e investigación. Fue fundamental. Despertaste al investigador que llevaba dentro de mí, avivando una pasión aún mayor por el campo. Agradezco tu estilo relajado y tu inspiradora forma de enseñar. Lo mejor de todo es que, además de un profesor, gané un gran amigo.

Tengo un profundo respeto y agradecimiento por mi orientadora en Brasil, Josicleda Domiciano Galvinicio, por su visión e incentivo desde el comienzo de mi trayectoria académica. Su apoyo incansable y su generosa compartición de conocimiento me guiaron hacia el máster y, posteriormente, hacia el doctorado. Su participación en mi camino hacia la Universidad de Granada fue crucial y nunca será olvidada.

A la profesora Edvânia Torres Aguiar Gomes, mi gratitud es inconmensurable. Sus lecciones trascendieron el ámbito académico y se convirtieron en un catalizador de transformación personal, moldeándome como ser humano. Su habilidad para abordar conceptos filosóficos y metodológicos de manera cautivadora y profunda abrió nuevos horizontes de comprensión en mi vida. A través de su orientación, comprendí la importancia crucial de la conciencia de clases y la relevancia de comprender en qué clase nos encontramos y por cuál debemos luchar. Sus palabras penetraron en mi mente y corazón, incitando una comprensión más profunda de las estructuras sociales y desigualdades que impregnan nuestra sociedad. Gracias a sus lecciones, aprecié la importancia de la lucha colectiva y el valor de nuestra fuerza de trabajo como base de nuestras vidas.

Mi amiga Mariko Carneiro merece un agradecimiento especial por su constante apoyo durante mi trayecto en el doctorado. Sus experiencias en su doctorado en Portugal aportaron valiosas perspectivas a mi recorrido, y sus consejos fueron invaluables para la conclusión de esta tesis.

A mi amiga y profesora Sayonara Elizario, le agradezco por su orientación y apoyo desde el inicio de mi búsqueda del doctorado. Su contribución fue crucial para mi decisión de estudiar en España y su acompañamiento ha sido fundamental en mi proceso de estudio.

Por último, extiendo mi agradecimiento al cuerpo docente y administrativo del Departamento de Ingeniería Civil de la Universidad de Granada. Su cálida bienvenida y apoyo continuo convirtieron mi estancia en Granada en una experiencia enriquecedora y gratificante.

Cada uno de ustedes ha dejado una marca perdurable en mi recorrido y ha contribuido a este momento significativo. A todos ustedes, les expreso mi profunda gratitud por creer en mí y hacer posible este logro.

AGRADECIMENTOS

Gostaria de expressar a minha sincera gratidão a todas as pessoas que desempenharam um papel fundamental na jornada que culminou na conclusão desta tese. Este trabalho não apenas reflete o meu esforço, mas também o apoio inestimável e as orientações generosas de muitos indivíduos notáveis.

Primeiramente, aos meus queridos pais, agradeço de todo coração por me guiarem desde a minha infância com a sábia lição de que a educação é o alicerce do sucesso. Suas palavras ecoaram ao longo dos anos e me motivaram a persistir, lembrando-me de que o conhecimento é o poder que nos conduz para além de nossos limites. Sem o seu amor e encorajamento, eu não teria chegado tão longe.

Ao meu companheiro incansável de todas as horas, Rafael Câmara Norat, minha gratidão é profunda e duradoura. Seu apoio constante e confiança em minhas ideias, mesmo quando pareciam ousadas demais no início, foram a força que me impulsionou. Você esteve ao meu lado, entendendo o meu potencial e encorajando-me a seguir em frente. Sua capacidade de elevar minha autoestima e oferecer apoio emocional fez toda a diferença em minha trajetória, permitindo-me superar desafios e realizar conquistas que jamais imaginei.

Ao meu orientador da Espanha, Angel Firmin Ramos Ridao, sou imensamente grato por sua orientação transformadora. Sua acolhida calorosa em seu país e a oportunidade de aprender e crescer em Andaluzia, especialmente em Granada, são lembranças que guardarei para sempre em meu coração. Angel, sua orientação não apenas no aspecto acadêmico, mas também em como investigar e ser um profissional comprometido na área da educação e pesquisa, foi fundamental. Você trouxe à tona o pesquisador em mim, despertando uma paixão ainda maior pela área. Agradeço pela sua descontração e pelo seu jeito inspirador de ensinar. O melhor de tudo foi que além de um professor eu ganhei um grande amigo.

Agradeço com profundo respeito à minha orientadora no Brasil, Josicleda Domiciano Galvinicio, por sua visão e incentivo desde o início de minha jornada acadêmica. Seu apoio incansável e seu compartilhamento generoso de conhecimento me guiaram em direção ao mestrado e, posteriormente, ao doutorado. Sua participação em meu caminho para a Universidade de Granada foi crucial e nunca será esquecida.

À professora Edvânia Torres Aguiar Gomes, minha gratidão é imensurável. Suas lições transcenderam o âmbito acadêmico, pois foi um catalisador de transformação pessoal, transformando-me como ser humano. Sua habilidade de abordar conceitos filosóficos e metodológicos de maneira envolvente e profunda abriu novos horizontes de compreensão em minha vida. Através de sua orientação, entendi a importância crucial da consciência de classes e a relevância de compreender qual classe ocupamos e por qual devemos lutar. Suas palavras penetraram em minha mente e coração, incitando uma compreensão mais profunda das estruturas sociais e das desigualdades que permeiam nossa sociedade. Com suas lições, compreendi a importância da luta coletiva e do valor de nossa força de trabalho como base de nossas vidas.

Minha amiga Mariko Carneiro merece um agradecimento especial por seu constante apoio durante meu percurso no doutorado. Suas experiências no doutoramento em Portugal trouxeram valiosas perspectivas à minha jornada, e suas dicas e conselhos foram inestimáveis para a conclusão desta tese.

À minha amiga e professora Sayonara Elizario, agradeço por sua orientação e apoio desde o início de minha busca pelo doutorado. Sua contribuição foi crucial para minha decisão de estudar na Espanha e seu acompanhamento tem sido fundamental em meu processo de estudo.

Por fim, estendo meu agradecimento ao corpo docente e administrativo do Departamento de Engenharia Civil da Universidade de Granada. Sua acolhida calorosa e suporte contínuo tornaram minha estadia em Granada uma experiência enriquecedora e gratificante.

Cada um de vocês deixou uma marca duradoura em minha jornada e contribuiu para este momento significativo. A todos, expresso minha profunda gratidão por acreditarem em mim e por tornarem possível esta conquista.

UNIVERSIDAD DE GRANADA

UNIVERSIDADE FEDERAL DE PERNAMBUCO

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DOCTORAL THESIS

to obtain

DOCTOR AT THE UNIVERSITY OF GRANADA AND DOCTOR AT THE FEDERAL UNIVERSITY OF PERNAMBUCO

DIOGO DA FONSECA SOARES

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2023

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ABSTRACT

The emission of greenhouse gases (GHGs) is an urgent environmental issue with significant implications for global climate change. Historically, the transportation sector has been a significant contributor to GHG emissions due to the predominant use of fossil fuels in vehicles. However, the railway system is widely recognized for being a more carbon-efficient mode of transportation compared to road and air transport.

Nevertheless, despite the relative advantages of the railway system in terms of GHG emissions, there are still challenges to be addressed. The expansion and modernization of railway networks, especially in developing regions, may require substantial investments in infrastructure and technology, which should be considered within the context of a sustainable approach.

In this context, this study conducted a retrospective bibliometric analysis spanning two decades in the railway sector, from 2002 to 2021, with the aim of deepening the understanding of the nuances of research in this field. To achieve this, the VOSviewer tool was employed to map connections between studied variables, revealing a marked increase in publications over this period. The standout work was that of Zhang, Y.T., identified as the most prolific author. The focus predominantly lay in engineering, with the Transportation Research Record being the most published journal. The leadership in this field was attributed to China, notably from the Southwest Jiaotong University. However, a gap in research regarding environmental impact and sustainability in railway systems was emphasized, pointing towards a promising area for future investigation.

Based on the bibliometric analysis, the urgency for further exploration in the realms of sustainability and environmental impact in railway systems became evident. The study was directed towards the railway system in northeastern Brazil, aiming to assess the greenhouse gas (GHG) emissions associated with this system and juxtapose them with relevant international studies. Its core scope was to establish parameters for GHG emissions from this system and formulate effective mitigation strategies.

To accomplish this goal, a comprehensive Life Cycle Assessment (LCA) approach was employed, providing meticulous scrutiny of the entire lifecycle of the railway system. This encompassed the collection of real data to construct a detailed inventory of GHG emissions. Furthermore, a comparison of GHG emissions in different urban railway transportation systems was conducted, yielding valuable contextual perspectives.

The results indicated that the total GHG emissions from the northeastern Brazilian railway system reached 11,996.11 tCO2e. Projections for a 50-year lifecycle estimated a total of 59,980,550 tCO2e of GHG emissions over the operational and maintenance cycle of the system.

The study also highlighted the Sustainable Water and Energy Consumption Program (SWEC), established to address supply challenges in a Brazilian railway company. The program succeeded in reducing per capita water and energy consumption by 10% and 19%, respectively, and included the installation of photovoltaic systems, resulting in an average 56% reduction in energy consumption in 2022 and a 50% reduction in greenhouse gas emissions.

Therefore, the railway system offers a valuable opportunity to decrease GHG emissions in the transportation sector. Electrification, the implementation of cleaner technologies, and operational optimization can contribute to mitigating these effects. However, it is important to adopt a holistic approach, considering all aspects of the railway system's value chain, in order to achieve more significant results in reducing GHG emissions and promoting environmental sustainability.

This study not only demonstrates an effective approach to challenges related to water and energy consumption but also contributes to the global sustainability objectives outlined in the UN's 2030 Agenda. Its interdisciplinary emphasis underscores the importance of reducing air pollution and fostering sustainable practices, especially within the context of climate change and public policies. In a scenario where sustainability and climate change mitigation gain crucial relevance, this study plays a significant role in sustainable development, paving the way for a more sustainable railway transportation system through Life Cycle Assessment and an interdisciplinary approach.

RESUMEN

La emisión de gases de efecto invernadero (GEI) es una cuestión ambiental apremiante que tiene implicaciones significativas en el cambio climático global. Históricamente, el sector del transporte ha sido un contribuyente importante a las emisiones de GEI debido al uso predominante de combustibles fósiles en los vehículos. Sin embargo, el sistema ferroviario es ampliamente reconocido por ser una forma de transporte más eficiente en términos de emisiones de carbono en comparación con los modos de transporte por carretera y aéreo.

No obstante, a pesar de las ventajas relativas del sistema ferroviario en términos de emisiones de GEI, todavía existen desafíos por enfrentar. La expansión y modernización de las redes ferroviarias, especialmente en regiones en desarrollo, pueden requerir inversiones significativas en infraestructura y tecnología, lo que debe considerarse en el contexto de un enfoque sostenible.

En este contexto, este estudio realizó un análisis bibliométrico retrospectivo que abarca dos décadas en el sector ferroviario, desde 2002 hasta 2021, con el propósito de profundizar en la comprensión de los matices de la investigación en este campo. Para lograr esto, se utilizó la herramienta VOSviewer para mapear conexiones entre las variables estudiadas, revelando un marcado aumento en las publicaciones a lo largo de este período. El trabajo destacado fue el de Zhang, Y.T., identificado como el autor más prolífico. El enfoque predominante fue en la ingeniería, siendo el Transportation Research Record la revista más publicada. El liderazgo en este campo correspondió a China, notablemente con la Southwest Jiaotong University. Sin embargo, se resaltó una brecha en la investigación relacionada con el impacto ambiental y la sostenibilidad en los sistemas ferroviarios, señalando hacia un campo prometedor de investigación futura.

Basado en el análisis bibliométrico, emerge la urgencia de una mayor exploración en las esferas de la sostenibilidad e impacto ambiental en los sistemas ferroviarios. El estudio se centró en el sistema ferroviario del noreste de Brasil, buscando evaluar las emisiones de gases de efecto invernadero (GEI) asociadas con este sistema y compararlas con estudios internacionales relevantes. Su alcance central consistió en establecer parámetros para las emisiones de GEI de este sistema y formular estrategias de mitigación efectivas.

Para cumplir con este objetivo, se empleó un enfoque integral de Evaluación del Ciclo de Vida (ACV), proporcionando un minucioso escrutinio de todo el ciclo de vida del sistema ferroviario. Esto implicó la recopilación de datos reales para construir un detallado inventario

de emisiones de GEI. Además, se realizó una comparación de las emisiones de GEI en diferentes sistemas de transporte ferroviario urbano, brindando valiosas perspectivas contextuales.

Los resultados indicaron que las emisiones totales de GEI del sistema ferroviario del noreste de Brasil alcanzaron 11.996,11 tCO_2e. Las proyecciones para un ciclo de vida de 50 años estimaron un total de 59.980.550 tCO_2e de emisiones de GEI a lo largo del ciclo operativo y de mantenimiento del sistema.

El estudio también resaltó el Programa de Consumo Sostenible de Agua y Energía (SWEC), creado para abordar desafíos de abastecimiento en una empresa ferroviaria brasileña. El programa logró reducir el consumo per cápita de agua y energía en un 10% y 19%, respectivamente, e incluyó la instalación de sistemas fotovoltaicos, lo que resultó en una reducción promedio del 56% en el consumo de energía en 2022 y un 50% en la emisión de gases de efecto invernadero.

Por lo tanto, el sistema ferroviario ofrece una valiosa oportunidad para reducir las emisiones de GEI en el sector del transporte. La electrificación, la implementación de tecnologías más limpias y la optimización operativa pueden contribuir a mitigar estos efectos. Sin embargo, es importante adoptar un enfoque holístico, considerando todos los aspectos de la cadena de valor del sistema ferroviario, con el fin de lograr resultados más significativos en la reducción de las emisiones de GEI y en la promoción de la sostenibilidad ambiental.

Este estudio no solo demuestra un enfoque efectivo para los desafíos relacionados con el consumo de agua y energía, sino que también contribuye a los objetivos globales de sostenibilidad delineados en la Agenda 2030 de la ONU. Su énfasis interdisciplinario subraya la importancia de reducir la contaminación del aire y fomentar prácticas sostenibles, especialmente en el contexto del cambio climático y las políticas públicas. En un escenario en el que la sostenibilidad y la mitigación del cambio climático adquieren relevancia crucial, este estudio desempeña un papel significativo en el desarrollo sostenible, allanando el camino hacia un sistema de transporte ferroviario más sostenible a través de la Evaluación del Ciclo de Vida y un enfoque interdisciplinario.

RESUMO

A emissão de gases de efeito estufa (GEE) é uma questão ambiental premente que tem implicações significativas nas mudanças climáticas globais. Historicamente, o setor de transporte tem sido um contribuinte significativo para as emissões de GEE devido ao uso predominante de combustíveis fósseis em veículos. No entanto, o sistema ferroviário é amplamente reconhecido por ser uma forma de transporte mais eficiente em termos de emissões de carbono em comparação com os modos de transporte rodoviário e aéreo.

No entanto, apesar das vantagens relativas do sistema ferroviário em termos de emissões de GEE, ainda existem desafios a serem enfrentados. A expansão e modernização de redes ferroviárias, especialmente em regiões em desenvolvimento, podem requerer grandes investimentos em infraestrutura e tecnologia, o que deve ser considerado no contexto de uma abordagem sustentável.

Neste contexto este estudo realizou uma análise bibliométrica retrospectiva abrangendo duas décadas no setor ferroviário, de 2002 a 2021, com o intuito de aprofundar a compreensão das nuances da pesquisa nesse campo. Para tal, utilizou a ferramenta VOSviewer para mapear conexões entre variáveis estudadas, revelando um marcante aumento nas publicações ao longo desse período. O trabalho de destaque foi o de Zhang, Y.T., identificado como o autor mais prolífico. Predominou o enfoque em engenharia, sendo o Transportation Research Record o periódico com maior publicação. A liderança desse campo ficou a cargo da China, notadamente com a Southwest Jiaotong University. Contudo, salientou-se a lacuna concernente à pesquisa do impacto ambiental e sustentabilidade nos sistemas ferroviários, apontando para um campo promissor de investigação futura.

Com base na análise bibliométrica, emerge a urgência por mais exploração nas esferas de sustentabilidade e impacto ambiental em sistemas ferroviários. O estudo direcionou-se ao sistema ferroviário do nordeste do Brasil, buscando avaliar as emissões de gases de efeito estufa (GEE) correlacionadas a esse sistema e cotejá-las com estudos internacionais relevantes. Seu escopo central consistiu em estabelecer parâmetros para as emissões de GEE desse sistema e formular estratégias de mitigação eficazes.

Para cumprir tal desiderato, empregou-se uma abordagem ampla de Avaliação do Ciclo de Vida (ACV), proporcionando um escrutínio minucioso sobre todo o ciclo de vida do sistema ferroviário. Isso englobou a coleta de dados reais para construir um inventário meticuloso de emissões de GEE. Ademais, procedeu-se à comparação das emissões de GEE em distintos

sistemas de transporte ferroviário urbano, conferindo valiosas perspectivas contextuais.

Os resultados consignaram que as emissões totais de GEE do sistema ferroviário do nordeste do Brasil atingiram 11.996,11 tCO2e. Projeções para uma vida útil de 50 anos estimaram um total de 59.980.550 tCO2e de emissões de GEE ao longo do ciclo operacional e de manutenção do sistema.

A pesquisa também destacou o Programa de Consumo Sustentável de Água e Energia (SWEC), criado para enfrentar desafios de abastecimento em uma empresa ferroviária brasileira. O programa conseguiu reduzir o consumo per capita de água e energia em 10% e 19%, respectivamente, e incluiu a instalação de sistemas fotovoltaicos, que levaram a uma redução média de 56% no consumo de energia em 2022 e 50% na emissão de gases de efeito estufa.

Portanto, o sistema ferroviário oferece uma oportunidade valiosa para reduzir as emissões de GEE no setor de transporte. A eletrificação, a implementação de tecnologias mais limpas e a otimização operacional podem contribuir para a mitigação desses efeitos. No entanto, é importante adotar uma abordagem holística, considerando todos os aspectos da cadeia de valor do sistema ferroviário, a fim de alcançar resultados mais significativos na redução das emissões de GEE e na promoção da sustentabilidade ambiental.

Este estudo não apenas demonstra uma abordagem eficaz para os desafios relacionados ao consumo de água e energia, mas também contribui para os objetivos globais de sustentabilidade delineados na Agenda 2030 da ONU. Sua ênfase interdisciplinar ressalta a importância de reduzir a poluição atmosférica e fomentar práticas sustentáveis, especialmente dentro do contexto das mudanças climáticas e políticas públicas. Em um cenário em que a sustentabilidade e a mitigação das mudanças climáticas adquirem relevância crucial, este estudo desempenha um papel significativo no desenvolvimento sustentável, apontando o caminho para um sistema de transporte ferroviário mais sustentável através da Avaliação do Ciclo de Vida e de uma abordagem interdisciplinar.

INTRODUCTION, BACKGROUND AND OBJECTIVE

The increasing demand for natural resources by humans has led to a growing concern regarding the impact of consumption on levels of emissions of polluting gases into the atmosphere, as well as the direct link between human activities, waste generation, and climate change. With the rising population, the consumption of goods and services in expansive urban areas requires even greater quantities of resources, both in terms of energy and land (Gassner et al., 2018).

The discussions surrounding climate change in recent years have been consistently highlighted across various channels of civil society, evoking concern from governments, the population, and scientists worldwide. These climate alterations may be linked to the increase in greenhouse gas (GHG) concentrations, which are responsible for the Earth's rising temperatures. GHGs primarily comprise carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF6), among others (Aminzadegan et al., 2022).

Transportation modes play a significant role in generating CO2 emissions and greenhouse gases. Emissions of air pollutants and greenhouse gases from the transportation sector continue to rise (Li et al., 2018b). Disregarding the significance of transportation would entail omitting crucial environmental impacts. Among these transportation modes, railway lines are widely used worldwide, albeit carrying their own environmental consequences (Ingrao et al., 2021).

The awareness that humans must take measures to reduce the impacts of their consumption is undeniable, and a shift in this pattern is imperative. Efforts must be undertaken to improve both the environment and psychological considerations related to the movement of goods from one location to another, especially over long distances.

Numerous countries are setting reduction targets, and the transportation sector is a focal point for sustainability enhancement. Europe aims to reduce greenhouse gas emissions by at least 60% by 2050 (Hegedic et al., 2018). Sweden aspires to achieve net-zero greenhouse gas emissions by 2045, requiring stakeholders in planning, construction, and transportation infrastructure to halve their impacts by 2030 (Liljenstrom et al., 2019). The Application of Life Cycle Assessment (LCA) in the transportation sector has witnessed significant growth in adoption and relevance in recent years. As awareness of the environmental implications of human activities increases, LCA emerges as a valuable tool for comprehensively assessing environmental impacts, particularly within transportation systems (Ramos da Silva et al., 2023, Hausberger et al., 2023, Keiser et al., 2023, Montoya-Torres et al., 2023).

LCA transcends the traditional approach of environmental impact analysis, which often focuses on a single life cycle phase or specific aspect of an activity. In contrast, LCA assesses environmental impact throughout the entire life cycle of a product or service, from raw material extraction, production, distribution, and use to final disposal. In the transportation sector, this encompasses vehicle and infrastructure manufacturing, daily operations, fuel consumption, emissions, and maintenance (Leichter et al., 2021, Gulcimen et al., 2021, de Bortoli et al., 2020).

The growing proliferation of LCA in the transportation sector is driven by several factors. Sustainability has become a global priority, prompting businesses and governments to seek ways to reduce their environmental footprint. LCA offers a comprehensive view of transportation-related environmental impacts, enabling the identification of critical points and areas for improvement (Ramos da Silva et al., 2023, Merchan et al., 2020, Gebler et al., 2020).

Moreover, consumers are becoming more environmentally conscious, demanding transparent information on the environmental footprint of products and services. LCA can provide this information clearly and objectively, empowering consumers to make informed decisions and choose more sustainable options (Keiser et al., 2023).

The application of LCA in the transportation sector can also drive innovation and the development of cleaner, more efficient technologies. The holistic analysis provided by LCA allows companies to identify opportunities for reducing greenhouse gas emissions, improving energy efficiency, and adopting more sustainable practices across the value chain (Da Fonseca-Soares et al., 2023, Jasti and Vinayaka Ram, 2021).

However, it is important to acknowledge that applying LCA in the transportation sector may present challenges, such as collecting accurate data throughout the entire life cycle and considering the complexities of interactions between different phases. Nevertheless, these challenges should not be seen as insurmountable obstacles but rather opportunities to enhance the methodology and achieve more reliable results (Da Fonseca-Soares et al., 2023, Lee et al., 2020, Li et al., 2018b).

To truly understand the impacts of these emissions, it is essential to comprehend how goods and services are consumed by society and measure the impacts they cause. To achieve a more precise understanding of these impacts, inventories are often conducted on all activities known to generate pollutants with high CO2 and GHG emissions, as well as solid waste generation. These inventories are conducted using tools such as life cycle assessment

(Aminzadegan et al., 2022, Wen and Wang, 2022).

The following table provides an adaptation of the state-of-the-art conducted by (Olugbenga et al., 2019), taking into account the studies conducted over the past 10 years.

Table 1. Reviewed Literature: Publication Title, Publication Authors, Railway Types, Functional Unit, Length, and Amortization Period of the Case Study

Author	**Publication Title**	**Country**	**Rail Type**	**Line Length (km)**	**Functional Units**	**Adopted Infrastructure Life (years)**
Chang e Kendall (2011)	Life Cycle Assessment of Greenhouse Gas Emissions from California High-Speed Rail Infrastructure Construction	USA/California	HSR	725	1PKT	60-100
Westin e Kågeson (2012)	Can High-Speed Rail Compensate for its Embodied Emissions?	Europe	HSR	500	1PKT	50
Chester *et al* (2012)	Life-Cycle Environmental Assessment of the Los Angeles Metro Orange Bus Rapid Transit and Light Rail Transit Lines	USA / LA	2*LIGHT	31.7	1PMT	30
Morita *et al* (2013)	*A Study on Methodology for Evaluating Environmental Load of Railway Infrastructure Construction*	Japan/Tokyo	LIGHT	33	1RIS	50
Yue *et al* (2015)	*Life Cycle Assessment of High-Speed Trains in China China*	China / Beijing	6* HSR	1318	1PKT	20
Hanson *et al* (2016)	Greenhouse Gas Emissions from Transit Rail Lines: Life Cycle Assessment of Materials Use	USA/ New Jersey	5*COMMUTER	6-196	1TMT	50
Lederer *et al* (2016)	Life Cycle Energy Demand and Greenhouse Gas Emissions of High-Capacity Urban Transportation Systems: A Case Study of Vienna U2 Metro Line	Austria / Vienna	LIGHT	14.8	1PKT	N/D
Li *et al* (2016)	Calculating the Life Cycle Greenhouse Gas Emissions of Urban Rail Transit Systems: A Case Study of Shanghai Metro	China / Shanghai	METRO	528	1OCL	50
Bueno *et al* (2017)	Environmental Performance Assessment of High-Speed Rail Projects in the Basque Country, Spain	Spain/ Basque Country	HSR	180	1PKT	60
Saxe *et al* (2017)	The Net Greenhouse Gas Impact of the Sheppard Subway	Canada / Toronto	METRO	5.5	1SS	N/D
Shinde *et al* (2018)	Life Cycle Assessment Based Comprehensive Environmental Performance Evaluation of Mumbai Suburban Railway, India	India / Mumbai	COMMUTER	983.8	1PKT	25
Chipindula *et al* (2021)	Life Cycle Environmental Impact of a High-Speed Rail System in the Houston-Dallas I-45 Corridor	USA/TEXAS	HSR	384.63	1PKT	N/D

Table adapted from Olugbenga; Kalyviotis e Saxe (2019)

2** signifies that two case studies were present in the publication. 3** signifies that three case studies were present in the publication. PKT (Passenger Kilometers Traveled); PMT (Passenger Miles Traveled); VKT (Vehicle Kilometers Traveled); TMT (Ton Miles Traveled); RIS (Rail Infrastructure System); MOB (Metro Over Bridge); CL (Construction Length Kilometers); SS (Subway System); HSR (High-Speed Rail).

One of the main methods of assessing the environmental impacts brought about by railway transportation is through the study of the Life Cycle Assessment (LCA), which is divided into four distinct phases: material extraction and processing, infrastructure construction, vehicle manufacturing, operation and maintenance of the system, and end-of-life (Liljenstrom et al., 2019, Wang et al., 2018, Li et al., 2018b, Soni and Chandel, 2018, Zhang et al., 2017a).

The quantitative analysis of railway network impacts, based on data collected across all phases of the system's life cycle, provides a solid foundation for developing strategies aiming to reduce costs and mitigate gas emissions, as evidenced by recent studies. A notable example is the research that assessed and compared greenhouse gas emissions throughout the life cycle associated with the four most common types of sleepers used in the UK railway network(Rempelos et al., 2020). This data-driven approach allows for a more precise understanding of the environmental impacts of the railway system and serves as a basis for formulating improvement strategies.

In a study conducted on the busy route between the cities of Dallas and Houston, which stands out as one of the most significant traffic corridors in the state of Texas, the analysis focused on evaluating the environmental impact of the high-speed rail (HSR) system along its life cycle. The study specifically addressed CO2 emissions and greenhouse gases associated with each vehicle, which were divided by the number of passengers and distance traveled. Each life cycle stage underwent a detailed analysis of emission sources and composition, enabling a comparison between the current railway system and the potential HSR system. In terms of energy use, the HSR proved to be 27% more efficient when compared to a passenger car (Chipindula et al., 2021).

To identify the critical phase for further investigation, it is essential to comprehend which phase consumes the most resources and consequently emits a higher amount of waste. According to the results obtained by (Chipindula et al., 2021, Li et al., 2018b), over 90% of emissions originate from the operation and maintenance phase. All these efforts share the same objective of guiding future endeavors toward emission reduction.

It is crucial to understand all the resources consumed throughout the life cycle of the railway system to measure the amount of CO2 and greenhouse gases generated during its operation. This knowledge will aid in identifying means for significant emissions reduction in railway transportation. The pace of technological advancements in transportation infrastructure construction should exceed that of the average urban economy to consistently decrease energy and carbon footprints of new projects being planned (Wei and Chen, 2020).

The increasing diffusion of LCA in the transportation sector reflects the need for more comprehensive and sustainable approaches to assess and mitigate environmental impacts. As awareness grows and demands for transparency increase, LCA emerges as a crucial tool to guide decision-making and promote sustainability in the transportation sector (Ramos da Silva et al., 2023, Hausberger et al., 2023, Keiser et al., 2023, Da Fonseca-Soares et al., 2023, Gulcimen et al., 2021).

Mapping the greenhouse gas emissions of the northeastern Brazilian railway system will assist the region in managing the environmental impacts of public transportation while enhancing environmental sustainability and aligning with state development.

On an economic level, defining activities associated with increased mobility and reduced environmental impact will characterize the process of sustainable development within the public transportation system. This characterization, contextualized with local peculiarities and potentialities, will outline measures and public policies to address national environmental challenges.

This study will also establish a theoretical-methodological framework for understanding the environmental impacts of public transportation activities and public policies for railway infrastructure development.

Various epistemological issues have been raised in the field of environmental management, aiming to overcome traditional scientific paradigms that do not accommodate the complex reality and reproduce the context of human insustainability. Interdisciplinarity is emphasized as a propelling element for adopting the systemic paradigm in scientific and strategic public policy development, thus impacting social dynamics.

Interdisciplinarity was an important parameter for designing this research project, understanding that studying the atmospheric impacts of the railway system will serve as a benchmark for shaping strategies and techniques for air pollution mitigation and improving the quality of life for future generations.

The objective of this study is to model greenhouse gas emissions from the northeastern railway system using Life Cycle Assessment (LCA) to comprehensively map resource inputs (materials, fuels, and equipment) and resulting emissions. This modeling is based on observed data from the railway system in the northeastern region of Brazil. Subsequently, the results obtained will be compared with case studies conducted globally to identify mitigation opportunities and propose actions to reduce the environmental impact resulting from emissions of these gases, aligning with Sustainable Development Goals (SDGs).

The urban railway transportation system in Brazil consists of tracks, viaducts, power installations, stations, vehicles, and control centers. The calculation will consider input resources (materials, fuels, and equipment) and greenhouse gas emission outputs in each of these phases.

To achieve this main objective, the following specific objectives are established:

1. Modeling and calculation of greenhouse gas emissions resulting from the metro-rail system in the northeastern region of Brazil;
2. Comparing the GHG emission results with other national and global case studies.
3. Proposing strategies to reduce greenhouse gas emissions from the metro-rail system in the northeastern region of Brazil to align with Sustainable Development Goals (SDGs) indicators.

CHAPTER 01

A BIBLIOMETRIC ANALYSIS ON TRENDS AND CHARACTERISTICS OF RAILWAY RESEARCH

The results presented in this chapter were published in the journal *Sustainability* (ISSN: 2071-1050)

Journal Rank Europe: JCR 3.9; CiteScore 5.8 - Q2 (*Environmental Studies*) /Q1 (*Geography, Planning and Development*)

Journal Rank Brazil: A2 (*Environmental Studies*) / A2 (*Engineering I*

1. Introduction

The railway system is the most efficient mode of human transportation since it serves as a mass transportation system for the general population and reduces traffic congestion in major cities. It is also useful for cargo logistics, allowing for the transport of a variety of cargo in large quantities and with minimal delay (Kostrzewski and Melnik, 2021).

Rail systems are a fundamental economic component of most countries, as they can transport millions of passengers and millions of dollars in goods from their origins to destinations every day. According to many empirical works and articles, rail transport, which produces very low CO2 emissions, is one of the most environmentally friendly and safest modes of transport (Larumbe, 2021, Zare et al., 2021, Gulcimen et al., Van Ryswyk et al., 2021, Boschiero et al., 2019, Chester et al., 2013, Chipindula et al., Ramanathan and Kalyan Kumar, 2013, Hamurcu and Eren, 2020, To et al., 2020, Nicola et al., 2010).

The expansion of rail networks is an important issue for the economic and social development of any country, as it enables revenue and jobs to be created sustainably and saves energy (Cuthill et al., 2019, To et al., 2020, Dolinayova et al., 2016).

People's commuting time may be spent contributing for society or doing something that would improve their quality of life. According to several studies, time saved on journeys to work is commonly invested in a revenue-generating activity (Abulibdeh, 2022, Whittington and Cook, 2019). In this respect, the railway system improves the people's capacity for movement, which is a fundamental right, while also providing more time for the population to dedicate to work or personal pursuits (Ferreira et al., 2021).

Human mobility is an incredibly important issue and as railway systems are a form of mass transport, many studies have been undertaken and many types of technology have been generated to improve the public image of these systems. Nevertheless, the popularity of , public rail transport is still low, despite the huge investments that it has received in recent decades (Masirin et al., 2017). Therefore, studying this system is extremely important to promote greater public acceptance. If the popularity of rail transport increased, the problems related to traffic could be reduced. This would have a positive environmental impact as buses, trucks, and cars significantly increase the emission of greenhouse gases. Rail travel produces much lower levels of emissions and its increased use could lead to urban improvement (Perez-Martinez et al., 2020).

Different factors associated with rail travel need to be improved and studied to improve railway systems and their relationship with urban planning. Some of these factors are: travel costs (Cools et al., 2016), quality of service, punctuality, number of connections, distances from stations to home or work, sustainability, energy efficiency (Kurczyński, 2021), renewable energy use (Carneiro and Soares, 2020), and high-speed trains (Cheng and Chu, 2021).

Therefore, a bibliometric analysis of the railway system sector is important to better understand what is being investigated and what gaps in the research exist so that they can be studied in the future. Current bibliometric research on railways exists that focuses on different areas. Some of these are: the socioeconomic impact of transport (Chen, 2022), logistics to explore current research on sustainable logistics technology for decision making in organizations (Qaiser et al., 2017), monitoring analysis of the state of the rail transport system to present updated content of the sensors used in this monitoring (Kostrzewski and Melnik, 2021), worker-railway relationships to explore the research using the human reliability tool (HRA) applied to the rail system (Ciani et al., 2022).

This study aims to examine the development of the field of bibliometrics by considering a 20-year period of global railway research to better understand the research that exists on railway systems. In order to outline the bibliometric research on railway systems and future research trends parameters were set by using questions:

Q1. What publication trends exist regarding rail systems?

Q2. What journals published the most articles about rail system?

Q3. Who contributes the most (authors, institutions, and countries) to the study of railway systems?

Q4. What are the main research areas on rail systems?

2. Materials and Methods

This methodology used in this study is bibliometric analysis, which is a technique for assessing the output of publications in a particular field of knowledge. It maps academic communities, and discovers networks of researchers and their different motivations (Kumar et al., 2020).

The bibliometric analysis can be achieved by developing indicators that summarize the most prolific institutions and authors, the most cited academics, and co-authorship networks regarding publications. The extraction of metadata to evaluate the progress of a field of knowledge over time is another method that is used. (Torraco, 2005, Cronin, 2001, Zhu and Guan, 2013, Kumar et al., 2020).

The articles search for the bibliometric analysis took place in January 2022, and was divided into four stages, as shown in Figure 1.

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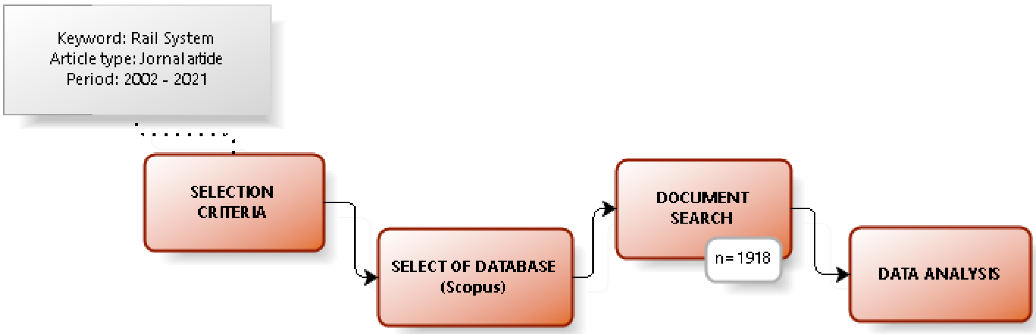

Figure 1. Stages of the articles search for the bibliometric analysis

Selection criteria: At this stage, the first criteria for the bibliometric search were defined: articles in the research field of "rail system" from the last 20 years (from 2002 to 2021).

Choice of Database: there are numerous types of databases for academic documents, however, Scopus was chosen for this study because it is a scientific database containing a large number of publications, authors, and journals that meet peer-reviewed scientific quality standards. (Martín-Martín et al., 2018, Martín-Martín et al., 2021, Ackerson and Chapman, 2003, Gabriel Junior et al., 2019, Prins et al., 2016).

Document search: The first search for "Rail System" resulted in 4,510 documents for the 20 year-timeframe. Following this search other filters were applied, and 1,918 documents met the criteria, as shown in Table 1 and. The final enter query string was:

TITLE-ABS-KEY ("rail system") AND (LIMIT-TO (PUBYEAR , 2021) OR LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2018) OR LIMIT-TO (PUBYEAR , 2017) OR LIMIT-TO (PUBYEAR , 2016) OR LIMIT-TO (PUBYEAR , 2015) OR LIMIT-TO (PUBYEAR , 2014) OR LIMIT-TO (PUBYEAR , 2013) OR LIMIT-TO (PUBYEAR , 2012) OR LIMIT-TO (PUBYEAR , 2011) OR LIMIT-TO (PUBYEAR , 2010) OR LIMIT-TO (PUBYEAR , 2009) OR LIMIT-TO (PUBYEAR , 2008) OR LIMIT-TO (PUBYEAR , 2007) OR LIMIT-TO (PUBYEAR , 2006) OR LIMIT-TO (PUBYEAR , 2005) OR LIMIT-TO (PUBYEAR , 2004) OR LIMIT-TO (PUBYEAR , 2003) OR LIMIT-TO (PUBYEAR , 2002)) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (PUBSTAGE , "final")).

Table 1. Summary of searches performed on the Scopus database

SEARCHES	KEYWORD	FILTER	RESULT	COMMENT
1st	Rail System		4,510	Not very discriminatory (Extremely high number of documents)
2nd	Rail System	Year: Between 2002 and 2021	3.,513	A 20-years dataframe was chosen as indicated by most authors for bibliometric analysis in this field of science
3rd	Rail System	Document type: Articles	1,943	Articles passes through peer-review, which indicates higher quality
4th	**Rail System**	**Publication stage: Final**	**1,918**	**Documents under publishing processes were not included.**

Data analysis: To develop the bibliometric analysis the data obtained from the Scopus database were examined. To determine the level of interest in the research are, it was analyzed the year of publishing, the journal, the area, the author and co-authors, the institution, the country, the keywords used in the research, the citation count, the H-index, and the article influence score from the Scimago Journal Rank (SJR).

Finally, the VOSwiever program was used to create network maps for each parameter, enabling word classification and analysis. (Bar-Ilan, 2010, Ciani et al., 2022, Kostrzewski and Melnik, 2021, Chen, 2022).

3. Results and Discussion

What publication trends exist regarding rail systems (Q1)?

This section summarizes the key characteristics of scientific production about “Rail system” in terms of the evaluation of the total number of articles (A), authors (AU), countries (C), citations (TC), average citation per article (TC/A), and journals (J). The analysis covered a 20-year period, from 2002 to 2021, which was separated into five-year periods to facilitate the analysis.

As a result, Table 2 presents the evolution of these articles' main characteristics. If we focus on the total number of articles published (A), it increased by abouts 56% in the second five-year period compared to the first, and by approximately 50% in the third five-year period compared to the second. In relation to the previous five-year period, the most recent five-year period increased by 20%.

Table 2. Characteristics of the scientific literature on railway systems.

YEAR	ARTICLES (A)	AUTHORS (AU)	COUNTRIES (C)	CITATIONS (TC)	TC/A	JOURNALS (J)
2002—2006	248	550	41	212	0.85	149
2007—2011	387	901	72	1535	3.97	242
2012—2016	583	1570	57	5824	9.99	325
2017—2021	700	1992	62	15334	21.91	381

(TC/A): Average citations per article

In overall, there is a 126% increase in the total number of articles published from the first five years of the study (2002-2006) to the last five years (2017-2021). Fig. 2 illustrates the exponential growth in the number of articles published during the previous 20 years.

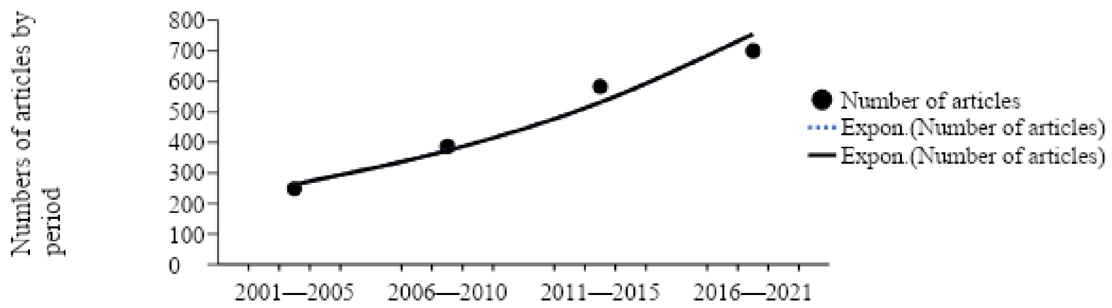

Figure 2. Trends of articles published on rail systems over the last two decades.

All other variables have likewise increased: authors (A), countries (C), citations (TC), citations per article (TC/A), and journals (J). The number of countries paying attention to the issue grew by nearly 50% in 20 years, from 41 to 62. The number of citations increased by 624% between 2002-2006 and 2007-2011, indicating a significant rise in interest in the research network during this time. The rise from 2007-2011 to 2012-2016 was 279%, while the increase from 2012-2016 to 2017-2021 was 163%.

The most significant increase in the number of journals (J) occurred from 2002-2006 to 2007-2011 (62%), followed by 34% from 2007-2011 to 2012-2016, and 17% from 2012-2016 to 2017-2021.

As a result, all of the indicators analysed indicates that there is a global interest in increasing research production in the topic.

Between 2002 and 2021, 27 areas of knowledge were researched, and Fig. 3 shows the five main thematic areas that Scopus included in these articles. Throughout the study period, the Engineering category received the highest research production, with a total of 1.243, accounting for 36,43% of the total, followed by Social Science (529, 15,50%), Environmental Science (222, 6,50%), Informatics (172, 5,04%), and Materials Science (165, 4, 83%). Furthermore, studies on rail system have been published in a variety of fields, reflecting the vast span of the research.

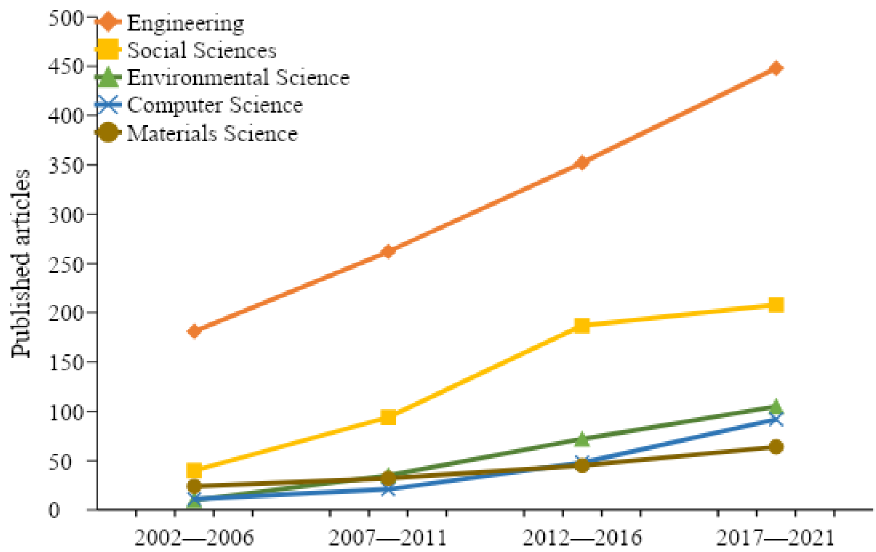

Figure 3. Evolution of the number of articles published on railway systems by subject area

What journals published the most articles about rail system (Q2)?

For this section, it was selected the 20 journals which published the most on rail system. The key characteristics of the articles published in these scientific journals are shown in Table 3. In the year 2020, 40% of them were in the first quartile (Q1) of the SJR index. These Q1 journals published 170 articles, accounting for 36% of all the articles published in this field in the top 20 journals. Moreover, journals in the second quartile (Q2) published 35% of all the articles published. The journals in the fourth quartile (Q4) accounted for 25% of the publication.

Table 3. Key features of articles published in the 20 journals with the highest scientific production.

Journals (J)	A	TC	TC/A	H	HJ	SJR	C	First Article	Last Article	Articles by five-year period			
										2002-2006	2007-2011	2012-2016	2017-2021
Transportation Research Record	70	608	8.69	15	119	0.62 (Q2)	United States	2015	2020	9	28	22	11
Neiranji Gongcheng Chinese Internal Combustion Engine Engineering	51	114	2.24	5	14	0.18(Q4)	China	2013	2021	10	13	20	8
Journal Of Transport Geography	39	1071	27.46	19	108	1.81 (Q1)	United Kingdom	2016	2021	3	6	17	13
Transportation Research Part A Policy And Practice	30	1471	49.03	16	133	2.18 (Q1)	United Kingdom	2014	2021	2	6	10	12
Tiedao Xuebao Journal Of The China Railway Society	27	152	5.63	7	30	0.40 (Q2)	China	2015	2021	0	4	11	12
Sustainability Switzerland	25	203	8.12	9	85	0.61 (Q1)	Switzerland	2018	2021	0	2	2	23
Proceedings Of The Institution Of Mechanical Engineers Part F Journal Of Rail And Rapid Transit	23	327	14.22	8	55	0.66 (Q2)	United Kingdom	2009	2021	1	3	4	15
Zhongguo Tiedao Kexue China Railway Science	21	140	6.67	8	27	0.44 (Q2)	China	2004	2021	7	4	2	8
Eb Elektrische Bahnen	18	30	1.67	3	12	0.10 (Q4)	Germany	2003	2018	10	3	3	2
Neiranji Xuebao Transactions Of CSICE Chinese Society For Internal Combustion Engines	18	51	2.83	4	18	0.16 (Q4)	China	2002	2020	6	3	5	4
Transport Policy	18	478	26.56	11	96	1.69 (Q1)	United Kingdom	2007	2021	0	2	8	8
Fuel	16	580	36.25	10	213	1.56 (Q1)	Netherlands	2005	2021	0	1	7	8
Research In Transportation Economics	14	128	9.14	6	46	1.02 (Q1)	United States	2007	2021	0	0	9	5
Transportation Research Part D Transport And Environment	14	202	14.43	8	99	1.60 (Q1)	United Kingdom	2011	2021	0	2	5	7
Urban Studies	14	677	48.36	10	147	1.92 (Q1)	United Kingdom	2005	2020	1	2	4	7
Planning	13	7	0.54	1	11	0.10 (Q4)	United States	2004	2018	1	6	4	2
Transportation Planning And Technology	13	155	11.92	7	42	0.43 (Q2)	United Kingdom	2004	2020	1	5	3	4
Urban Rail Transit	13	126	9.69	5	14	0.52 (Q2)	Germany	2015	2021	0	0	3	10
ZEV Rail Glasers Annalen	13	4	0.31	1	6	0	Germany	2002	2008	8	5	0	0
Energies	12	49	4.08	3	93	1.60 (Q2)	Switzerland	2015	2021	0	0	1	11

When we analyzed the impact factor, we observed that Fuel, from the Netherlands has the highest H-index between journals (HJ), followed by Urban Studies, from the United Kingdom.

The journals that published the largest number articles were Transportation Research Record, Neiranji Gongcheng Chinese Internal Combustion Engine Engineering, and the Journal of Transport Geography with 70 (15.09%), 51 (10.99%) and 39 (8.41%) articles published, respectively.

Around 55% of the journals showed continuity in their publication rates, with at least one articles every five years, which shows that railway systems were well studied during this period.

In the last five years, Sustainability (Switzerland) published the highest number articles on rail system. Because the journal's specialty is Environmental Sciences, this shows a tendency for studies on rail system and sustainability challenges. This might be tied to the growing concern about the effects of global climate change and the shortage of natural resources, both of which are causing increasing limits on economic activity, implying the need for continuous improvement in services and means of production (Tian et al., 2019).

Finally, it is worth noting that the largest number of journals come from the United Kingdom (40%) followed by China and the United States.

Who contributes the most (authors, institutions, and countries) to the study of rail systems? (Q3)

This subsection highlights the most productive individual authors, as well as their cooperation with their peers, focusing on co-authorship indicators. These indicators highlight the most productive institutions and nations, the co-authorship network, and the most successful international alliances.

Some of most prolific authors on the rail system between 2002 and 2021 are shown in Table 4. The author with the most works to his name is Zhang, YT, who published 15 articles and was cited 45 times during this period; he is followed by Ma, X. with 14 articles and 55 citations. Both authors share the same research quality indicator of H-index = 4; and Wang, P. who published 13 articles with 59 citations with a research quality indicator of H-index = 5. Pagliara, F. has fewer publications (9) to his name than the author in the highest position but has a research quality indicator of H-index = 5.

Table 4. The most prolific authors writing about rail systems between 2002 and 2021

Autores	A	TC	TC/A	Institution	C	1^{st} A	Last A	H-index
Zhang, Y.T.	15	45	3.00	Southwest Jiaotong University	China	2005	2018	4
Ma, X.	14	55	3.93	Beijing Jiaotong University	China	2013	2021	4
Wang, P.	13	59	4.54	Ministry of Education China	China	2013	2020	5
Ouyang, G.Y.	12	35	2.92	Beijing Institute of Technology	China	2005	2013	4
Fan, L.	11	22	2.00	Naval University of Engineering	China	2013	2021	3
Mulley, C.	11	272	24.73	Harbin Engineering University	China	2007	2019	2
Bai, Y.	10	21	2.10	Shanghai Jiao Tong University	China	2013	2021	3
Chen, G.X.	9	96	10.67	Tianjin University	China	2011	2021	5
Huang, Z.	9	65	7.22	Tongji University	China	2006	2018	4
Pagliara, F.	9	246	27.33	Newcastle University	United Kingdom	2009	2019	5

A): number of articles; (TC) number of citations; (TC/A): average number of citation per article; (C): country; (1^{st} A): first published article; (Last A): last article published; (H-index): Hirsch index for this author.

Among the top ten contributors, Pagliara, F. received the most citations per publication, (TC/A = 27.33) followed by Mulley, C. with (TC/A = 24.73). But it is important to note that the two authors who were cited the most were only in the tenth and sixth positions in terms of number of articles published (A). This shows that the number of publications did not relate to a good number of citations and that the indices (TC/A and A) for rail system field were not proportionate.

It is interesting to note 90% of the ten most prolific authors are from Chinese Institutions, and only one author from this group is from an Institution from the United Kingdom.

Around 40% of the most prolific authors (top ten) began to be published only in the third 5-year period of the 20 years research period, and only 40% of these authors were published in 2021.

Finally, Figure 4 displays the cooperation network between the key authors who had published on the rail system, based on the study of cooperation and the inclusion of at least three co-authorship publications, generating a total of 9 clusters and 91 authors. The colors symbolize the working groups, and the size of the circle varies according to the number of articles contributed by each autor.

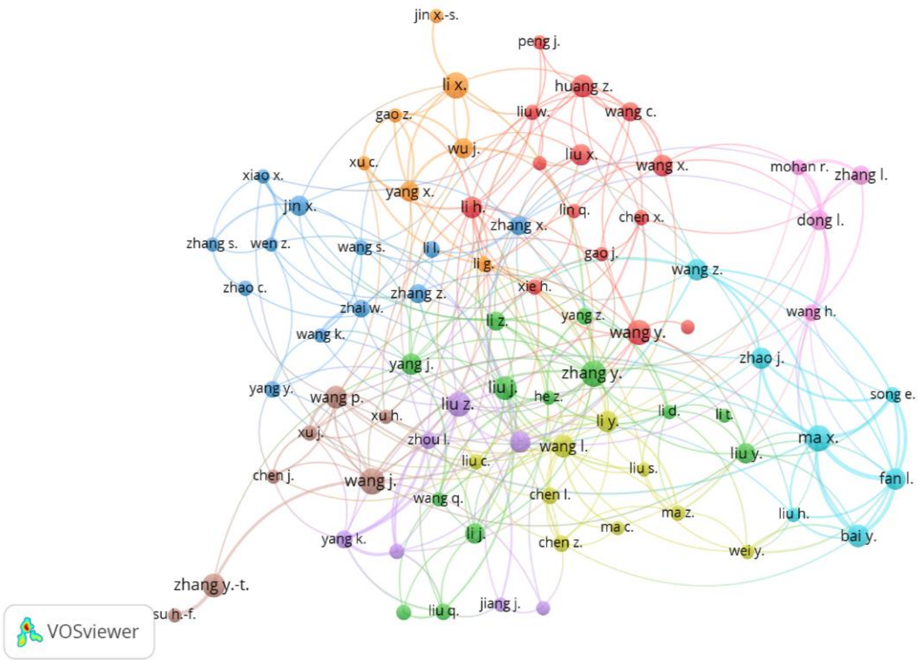

Figure 4. Co-authoring network of authors

The analysis of cooperation between authors helps us to discover the structure of cooperation between authors and institutions, as well as understand the links between researchers and how knowledge is spread, making it a useful analytical lens (Bar-Ilan, 2010). Partnerships can help spark new research by facilitating the exchange of ideas, and synergies can increase the number of opportunities for publication in high-quality journals (Kumar et al., 2020).

From the top ten most productive authors Mulley, C., Chen, G.X, and Pagliara, F. appeared in any of the network clusters, indicating that there is strong international cooperation in transportation systems. However, it is noted that interactions are much more frequent between authors from the same country, for example, we have authors from China who are mostly coauthors from the same country (China). Interaction with other international authors may promote the rapid growth of the research area and the dissemination of knowledge.

The institutions that published the most on rail systems between 2002 and 2021 are shown in Table 5. The Southwest Jiaotong University, with 106 articles and 987 citations publishes the most on rail systems. The second on the list is Beijing Jiaotong University with 68 articles and 568 citations, followed by the Chinese Ministry of Education with 37 articles and 213 citations.

Table 5. The most prolific institutions for the publications on rail systems between 2002 and 2021.

Institution	C	A	TC	TC/A	H index	IC (%)	TC/A	
							IC	NIC
Southwest Jiaotong University	China	106	987	9.31	17	12.3%	12.62	8.85
Beijing Jiaotong University	China	68	568	8.35	12	22.1%	16.87	5.94
Ministry of Education China	China	37	213	5.76	9	18.9%	10.57	4.63
Beijing Institute of Technology	China	35	108	3.09	6	5.7%	0.00	3.27
Naval University of Engineering	China	29	48	1.66	4	0.0%	0.00	1.66
Harbin Engineering University	China	26	75	2.88	5	26.9%	5.57	1.89
Shanghai Jiao Tong University	China	25	168	6.72	7	8.0%	11.50	6.30
Tianjin University	China	22	158	7.18	6	4.5%	0.00	7.52
Tongji University	China	21	120	5.71	6	14.3%	14.33	4.28
Newcastle University	United Kingdom	19	714	37.58	10	31.6%	20.33	45.54

(C): country (A): number of articles; (TC) number of citations (TC/A): average number of citations per article; (H-index): Hirsch index for this research area (IC%): percentage of article written through international cooperation; (IC): number of citations per article written through international cooperation; (NIC): number of citations per article written without any cooperation

Newcastle University, which appears in the last position on the list with only 19 publications, has the highest average number of citations per article (37.58). This is a result of the fact that even though it had fewer publications, its articles were highly cited.

The Southwest Jiaotong University and Beijing Jiaotong University are the ones with the highest research quality rating with H-indexes of 17 and 12, respectively. However, Newcastle University, despite its position regarding the number of publications, is in third position for research quality with a H-index of 10.

Nine of the ten most important institutions when considering work published in this study area are in China, with only one from the United Kingdom, which indicates China's prominence in worldwide publications on rail systems.

It is worth noting that all of the institutions considered have international cooperation rates that are less than 50%, indicating that the institutions have produced very few articles through international cooperation, corroborating the analysis shown in Figure 4 that most authors are publishing with others from the same country, and even from the same institution.

The total citations per article (TC/A) with international cooperation (IC) was higher than the total citations per article (TC/A) without international cooperation (NIC). It is extremely important to create international cooperation networks for research, as they could help research to have a greater impact by analyzing citations of articles written through international cooperation and without this cooperation, the disparity in the quantity of citations is notable. In some cases, articles that are written through a process of international cooperation are cited more than three times as often as those written without cooperation, as in the case of Beijing Jiaotong University, Harbin Engineering University, and Tongji University, which had more than three citations in articles that were published in an international partnership.

The countries which were most prolific in publishing work on rail systems between 2002 and 2021 are presented in Table 6. China and the United States emerge as the most prolific and important countries, since together they represent almost 80% of all the work published on this subject, with 571 articles and 4,145 citations; 361 articles, and 7,359 citations, respectively. The United Kingdom contributed with 168 articles and 3,799 citations, which leaves it in third place.

China, the United States, and the United Kingdom are the only countries that have contributed more than 100 articles each on rail systems. However, it is important to note that this is a subject which generates widespread interest and contributions to the field of study have come from many countries from different continents.

Table 6. Most prolific countries for the publication of articles on rail system between 2002 and 2021

Country	A	TC	TC/A	H index	R			
					2002-2006	2007-2011	2012-2016	2017-2021
China	571	4145	7.26	30	(1) 46	(1) 88	(1) 158	(1) 279
United States	361	7359	20.39	46	(5) 10	(2) 87	(2) 119	(2) 111
United Kingdom	168	3799	22.61	31	(2) 44	(3) 35	(3) 53	(3) 62
Germany	91	591	6.49	16	(4) 18	(4) 21	(8) 24	(9) 15
Italy	85	1479	17.40	22	(3) 31	(5) 13	(7) 25	(4) 37
Australia	70	1135	16.21	21	(7) 9	(7) 8	(4) 31	(5) 26
Spain	62	1075	17.34	18	(8) 5	(8) 8	(5) 26	(6) 23
Canada	55	881	16.02	18	(9) 5	(9) 8	(9) 16	(7) 21
South Korea	51	420	8.24	12	(6) 10	(10) 6	(6) 26	(10) 15
Taiwan	42	701	16.69	14	(10) 4	(6) 11	(10) 12	(8) 16

In terms of the evolution of the study area, China produced the greatest number of scientific research articles during the final five-year period, which illustrates its obvious ongoing development of scientific research on this issue.

The United Kingdom took second place in the first five-year period with 44 publications, but this country is losing production in comparison to the United States which took second place in the next five years and remained there until the end of 2020.

It is worth noting that, in the final five-year period, almost all the countries considered increased their research output on this subject, however Spain, Germany, and the United States are exceptions as their output decreased. China, which is at the top of the production ranking, doubled its publication rate in the final five-year period.

Table 7 shows the effective international networks and the metrics evolution of the countries which produced the most research on the study area during the period under consideration.

Table 7. Cooperation between different countries for research on rail systems between 2002 and 2021

Country	NC	Main collaborators	IC (%)	TC/A	
				IC	NIC
China	25	United States, United Kingdom, Hong Kong, Australia, Canada	16.8%	15.74	5.55
United States	34	United States, China, United Kingdom, Australia, Canada	27.1%	23.37	19.27
United Kingdom	27	China, United States, Australia, Italy, Germany	38.1%	28.59	18.93
Germany	14	United Kingdom, Germany, Spain, United States, Canada	22.0%	14.15	4.34
Italy	21	Austria, Italy, Spain, United Kingdom, Netherlands	30.6%	13.50	19.12
Australia	15	United Kingdom, United States, China, Canada, Iran	38.6%	20.41	13.58
Spain	11	Netherlands, United Kingdom, United States, Italy, France	33.9%	24.19	13.83
Canada	18	China, United States, Australia, Hong Kong, Italy	41.8%	16.04	16.00
South Korea	8	United States, India, Thailand, Malaysia, Singapore	27.5%	15.29	5.57
Taiwan	14	United States, Australia, Brazil, Hong Kong, Canada	23.8%	22.00	15.03

(NC): number of countries cooperating; (CI): percentage of countries involved in cooperatively created articles; (TC/P): number of citations per article; (IC): international cooperation; (NIC): non-international cooperation.

Canada took part in more cooperative work than any other countries, with a percentage of 41.8%, followed by Australia and the United Kingdom with 38.6% and 38.1%, respectively. However, China, which is the country with the highest number of publications, has the lowest number of international partnerships, ranking last at 16.8%.

Despite having a large number of international collaborators, all countries have a rate of international cooperation that is less than 50%. This means that more than half of their publications are written by authors from the same country. According to a citation analysis of articles, the value of citation increases significantly when there is international cooperation (IC x NIC).

Figure 5 illustrates a map of collaboration among the major countries based on coauthorship, with at least six interactions. It is represented by 9 clusters of different colors, the colors representing international work groups, and the size of the circle varies depending on the number of articles.

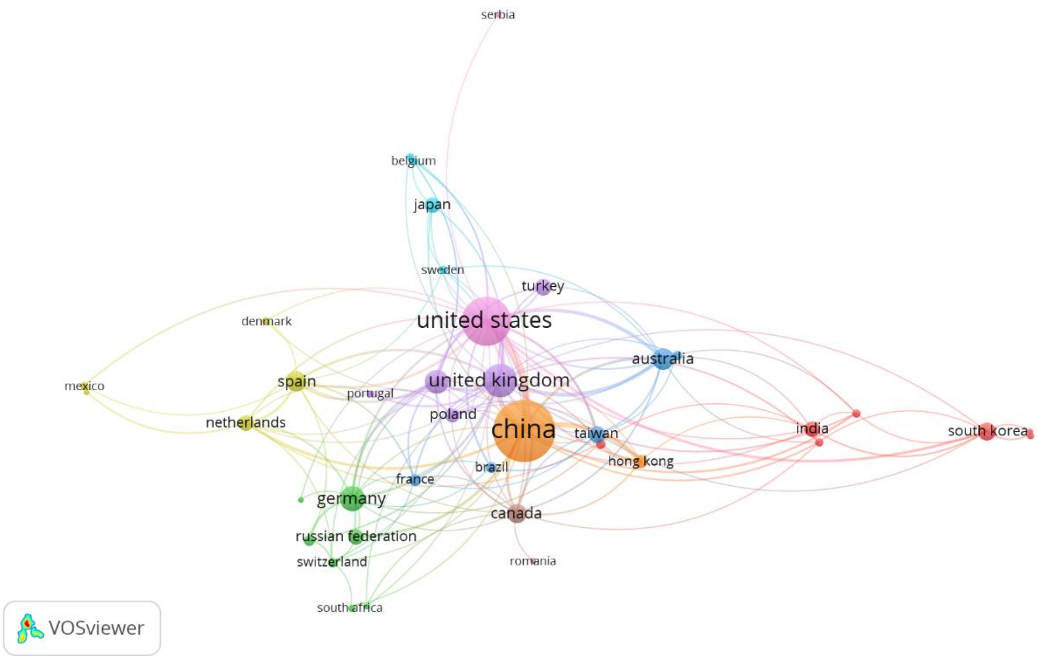

Figure. 5. International cooperation, based on international co-authorship.

The red and green cluster are the largest clusters. It is comprised of seven countries, which are led by led by India and South Korea, and Germany and Russia, respectively. This is followed by the blue, yellow and purple clusters, which are each comprised of five countries, and they are led by Australia, Spain, and the United Kingdom, respectively. The light blue cluster, which is comprised of four countries, is led by Japan, and finally the orange, brown and lilac clusters, which are each comprised of only two countries, are led by China Canada and the United States respectively.

Main research areas on rail systems (Q4)

In order to study rail systems, an analysis of the keywords was carried out. From the 1,914 articles on railway systems in the period between 2002 and 2021 that were analyzed, a total of 7,711 keywords were obtained.

Keywords represent the content of a document. Keyword analysis is a useful method for knowledge mining and gaining insight into the structure of knowledge and research trends. (Wang et al., 2020).

Table 8 lists the 20 keywords that were most relevant by the authors of this research, as they allow the interests that were generated in the line of research to be disaggregated. To facilitate in the analysis of key words, six thematic groups were applied.

Table 8. Keywords for rail systems

Group	Keyword	2002-2021		2002-2006		2007-2011		2012-2016		2017-2021	
		A	%	A	%	A	%	A	%	A	%
Sustainability and Rail Systems	Urban Development	37	1.9%	3	1.2%	7	1.8%	11	1.9%	16	2.3%
	Optimization	68	3.5%	7	2.8%	13	3.4%	21	3.6%	27	3.9%
	Light Rail	118	6.2%	3	1.2%	19	4.9%	26	4.5%	70	10.0%
	Environmental Impact	22	1.1%	4	1.6%	5	1.3%	8	1.4%	5	0.7%
Railway Mechanics	Common Rail System	92	4.8%	9	3.6%	17	4.4%	27	4.6%	39	5.6%
	Wheel-rail Systems	82	4.3%	9	3.6%	10	2.6%	18	3.1%	45	6.4%
	Finite Element Method	63	3.3%	8	3.2%	10	2.6%	18	3.1%	27	3.9%
	High-speed Train	78	4.1%	4	1.6%	10	2.6%	9	1.5%	20	2.9%
Urban Train Development	Accessibility	38	2.0%	1	0.4%	7	1.8%	12	2.1%	18	2.6%
	Public Transport	112	1.8%	12	4.8%	32	8.3%	22	3.8%	46	6.6%
	Rail Systems	180	9.4%	9	3.6%	82	21.2%	40	6.9%	49	7.0%
	Sustainability	38	2.0%	2	0.8%	6	1.6%	11	1.9%	19	2.7%
Maintenance	Urban Transport	132	6.9%	16	6.5%	27	7.0%	42	7.2%	47	6.7%
	Light Rail Transit	183	9.5%	19	7.7%	30	7.8%	64	11.0%	70	10.0%
	Transportation Infrastructure	51	2.7%	4	1.6%	6	1.6%	20	3.4%	21	3.0%
	Vibrations (mechanical)	92	4.8%	9	3.6%	15	3.9%	16	2.7%	52	7.4%
Energy Efficiency and Greenhouse Gases	Energy Use	34	1.8%	3	1.2%	5	1.3%	10	1.7%	16	2.3%
	Greenhouse Gases	20	1.0%	0	0.0%	5	1.3%	7	1.2%	8	1.1%
	High-speed Rail	31	1.6%	1	0.4%	4	1.0%	10	1.7%	16	2.3%
	Emission Control	20	1.0%	0	0.0%	4	1.0%	5	0.9%	11	1.6%
Combustion	Diesel Engines	245	12.8%	45	18.1%	56	14.5%	65	11.1%	79	11.3%
	High-Pressure Effects	24	1.3%	4	1.6%	3	0.8%	7	1.2%	10	1.4%
	High-Pressure Common Rail System	97	5.1%	6	2.4%	22	5.7%	32	5.5%	37	5.3%
	Fuel Injection	87	4.5%	21	8.5%	12	3.1%	23	3.9%	31	4.4%
	Total number of articles:	1.918		248		387		583		700	

The "maintenance" group is a thematic group that was studied in depth, with the keywords "Light Rail Transit" found in around 9.5% of publications. The evolution of this research increased over the years, and the largest number of articles published on this subject were found in the 2017-2021 period.

Urban transport development, train maintenance, and combustion are the areas that were studied the most and were written about the most. From these three sections, the development of urban transport is the area on which the most research has been published.

According to the dimensioning of the group " Energy Efficiency and Greenhouse Gases" the environment continues to be a neglected area by researchers. Sustainability, environmental effect, and climate change are topics that are rarely addressed in railway research. However, the last five years have seen a significant rise in study in this field.

Figure 6 illustrates the rail system keywords that were used in the 20-year period considered based on the co-occurrence method. Keywords with at least five interactions were chosen. Keywords identify the major points of a study and describe research subjects in a certain field. The close links between terms are represented by their co-occurrence.

The exploration of important research subjects and emerging research trends using the co-occurrence of these terms is a very successful research strategy. (Rajeswari, S. et al., 2021). By using VOSviewer, a visual representation of networks based on distance was generated, where the distance between two nodes denotes the degree of their proximity. By using this approach. keywords in our search domain could be identified (Rajeswari et al., 2021).

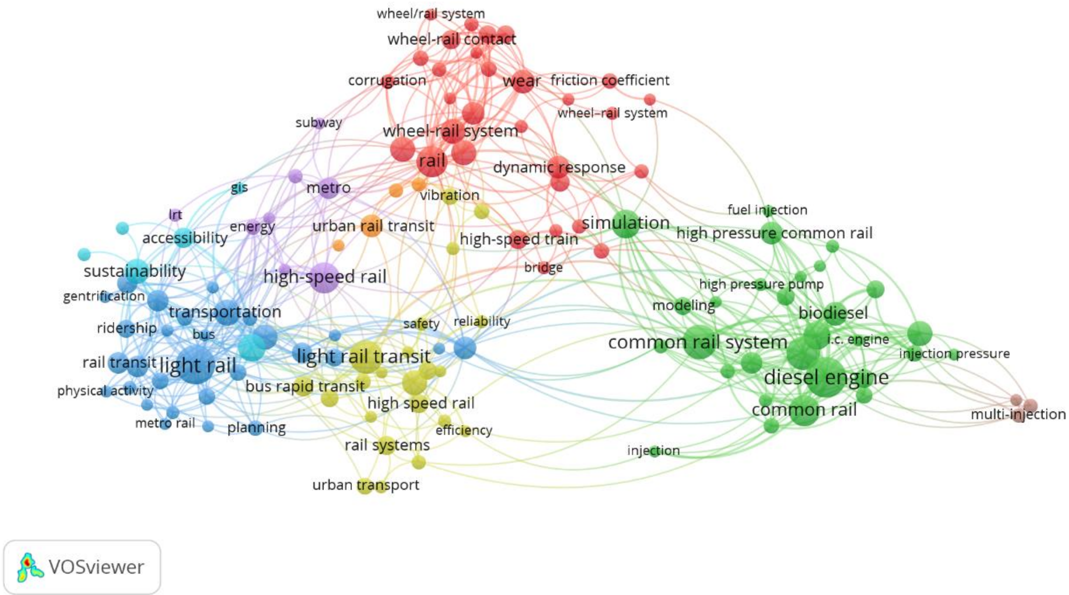

Figure 6. Keywords in co-occurrence-based rail system publications.

The red cluster which has the highest number of keywords (30) refers to the study of the mechanical engineering trains, which main objective is to research improvement in the mechanical movement of the railway system.

Many studies focus on steps such as computer simulation or the development of new technologies to improve the process of wave patterns, friction in the contact zone, vibration, and dynamic component distribution patterns during the train's movement over the railway to obtain more speed, improved performance, safety, and performance of the locomotor. (Kozhemyachenko et al., 2020, Kozhemyachenko et al., 2021, Keropyan, 2021, Wei et al., 2019a, Chen et al., 2016a, Chen and Zegras, 2016, Wang et al., 2015, Wang et al., 2014, Wang et al., 2008, Liu et al., 2011, Xue and Zhang, 2014, Chen et al., 2016b, Jiang et al., 2015).

The green cluster, with 29 keywords, refers to the study of engines, energy consumption, new sustainable types of fuel (Li et al., 2018a), new types of combustion systems (Liu et al., 2019, Feng et al., 2021), biodiesel (Pawlak et al., 2021), natural gas (Wierzbicki, 2018), and liquefied petroleum gas (Zöldy et al., 2021). Many articles presented research focused on internal combustion engines, which is a heat engine in which the combustion of a fuel with an oxidant takes place in a combustion chamber that is an integral part of the working fluid flow circuit. Basically, in an engine, chemical energy is transformed into thermal energy through fuel combustion, and this thermal energy is transformed into mechanical energy that is used to perform train movement (Chen et al., 2012). These studies focus on new engine models, such as multi-fuel, biofuel, and water-powered engines. Research can also be found that aims to improve diesel engine pressure by using simulation and modeling (Meng et al., 2010, Zhang et al., 2008, Chen et al., 2009, Xu et al., 2009, Chen et al., 2012).

The dark blue with 29 keywords, addresses research in the area of urban passenger trains, urban planning (Hensher et al., 2015b, Hensher et al., 2015a), light vehicle performance (Zimny-Schmitt and Goetz, 2020), and new technologies to improve the energy efficiency of light vehicles (Sovacool and Yazdi, 2019), the relationship between the public and trains (Roberts et al., 2018, Brown et al., 2019), and investment in public urban transport policies (Olesen, 2020, D. Knowles and Ferbrache, 2016).

The yellow cluster with 22 keywords represents the areas of both preventive and predictive maintenance to ensure passenger safety (Karakose and Yaman, 2020), rail system efficiency as a calculation of nodal capacity utilization rates, capacity, railway station performance (Armstrong and Preston, 2017, Preston et al., 2017), the efficiency of the urban transport system (Couto, 2011), and transport regulation in different countries.

The purple cluster with only 8 keywords addresses the sustainable development of rail systems, such as reducing greenhouse gas emissions (Boarnet et al., 2018),life cycle analysis (Kaewunruen et al., 2020, Cheng et al., 2020), development of new types of sustainable energy, and the environmental impact of rail systems which mainly focuses on air pollution (Soni and Chandel, 2018, Mitchell et al., 2018). The environmental impact of railway systems has not been studied in depth, and therefore it is an area that presents new research opportunities.

The light blue cluster has only six keywords and investigates the sustainability index (Sekasi and Martens, 2021, Larumbe, 2021), accessibility of urban transport (Sarker et al., 2020) , and the lack of urban train accessibility different cities (Ferreira et al., 2020, Hong et al., 2020, Huang et al., 2017).

The orange cluster of keywords addresses the concept of improving urban trains, urban mobility, and urban planning as options for accessing and exiting urban rail transport (Wu et al., 2018).

Finally, the smallest cluster with only three keywords in brown interacts with the green cluster an refers to direct fuel injection systems, multi-material injection modeling, and modeling of restrictor valve performance and engine performance (Liu et al., 2010).

4. Conclusions

This work analyzed the evolution of research articles on railway systems with a 20-year global retrospective that covered the period between 2002 and 2021. Even though rail systems have been developed for centuries, the scientific production in this topic has started to grow only in the last 20 decades. This grow is followed by the increase in the number of journals, institutions and authors who publish on the subject, which demonstrates a recent increase in the scientific community´s interest in the theme. Most of the scientific productions comes from China, however a lot of research interaction was observed between other countries.

When analyzing authors, the researcher Zhang, Y.T. was found to be the most important one in the whole period, with 15 articles published. It is interesting to note that among the 10 authors who published the most, 9 are from Chinese institutions.

The study of the research areas reveals that, throughout the period analyzed, Engineering was the category that was studied the most between the rail system field, followed by Social Sciences and Environmental Sciences, Computer Science and Material Science.


CBTU

CHAPTER 02

LIFE CYCLE ASSESSMENT ON GREENHOUSE GAS EMISSIONS IN RAILWAYS: SYSTEMATIC REVIEW OF RESEARCH PROGRESS

The results presented in this chapter were published in the journal Journal of Cleaner Production
Journal Rank Europe: JCR 11.1; CiteScore 18,5 – Q1 (*Engineering, Multidisciplinary*)/Q1 (*General Engineering*)
Journal Rank Brazil: A1 (*Environmental Studies*) / A1 (*Engineering I*)

1. Introduction

The increase in concentrations of Greenhouse Gas Emissions (GGE) in the atmosphere has led to an amplified greenhouse effect, resulting in higher average temperatures worldwide. This global warming causes a range of adverse impacts on various aspects of the biosphere, from natural ecosystems to human activities (Tian et al., 2023).

Climate change represents one of the most pressing and complex challenges that humanity faces in the 21st century. It reflects significant changes in global climate patterns over time, primarily driven by human activity and its emissions of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)(Kwakwa et al., 2023). International cooperation plays a crucial role in addressing climate change, as evidenced by the Paris Agreement, a global milestone aimed at limiting global warming well below 2°C compared to pre-industrial levels. Individual efforts, governmental actions, and corporate commitments are also essential to tackle this challenge (Ogunkunbi and Meszaros, 2023).

Europe, for instance, is significantly impacted by climate change, presenting a series of environmental, social, and economic challenges for the region. These impacts are observed in various areas and have profound implications for European countries and the continent as a whole (Christian et al., 2023, Sasse and Trutnevyte, 2023). To address these challenges, the European Union and its member states are implementing policies and actions to mitigate and adapt to climate change. The Paris Agreement, which the European Union has joined, sets goals to limit global warming and reduce greenhouse gas emissions. Investments in sustainable technologies, promotion of energy efficiency, protection of natural ecosystems, and public awareness are key strategies (Poppe Terán et al., 2023, Nainggolan et al., 2023).

In light of this panorama, climate change mitigation has become a global priority. This involves reducing greenhouse gas emissions through transitioning to renewable energy sources, increasing energy efficiency, conserving natural resources, and adopting sustainable consumption practices. Furthermore, adaptation is equally crucial, involving the implementation of strategies to address ongoing impacts and the development of resilient infrastructures. It's important to emphasize that climate change knows no borders, and international cooperation is essential to address this global challenge. Europe plays an active role on the international stage, working together with other countries to build a more sustainable and resilient future in the face of climate change (Aminzadegan et al., 2022, Fageda, 2021).

Furthermore, climate change disproportionately affects vulnerable populations, such as low-income communities, indigenous peoples, and densely populated coastal regions. Lack of access to resources, adequate infrastructure, and early warning systems increases their susceptibility to extreme weather events, exacerbating existing inequalities and creating new socio-economic challenges. This reality underscores the urgency of addressing climate change not only as an environmental issue but also as a matter of social justice and human rights (Chen, 2022, Ren et al., 2020).

In summary, climate change represents a global crisis that impacts all aspects of life on Earth. It requires immediate and coordinated action to reduce greenhouse gas emissions, adapt to ongoing impacts, and build a more sustainable and resilient future. Awareness, education, and cooperation are essential to confront this threat and ensure a healthy and habitable planet for present and future generations(Gulcimen et al., 2021, Ren et al., 2020, Dolinayova et al., 2016).

Therefore, the study of Greenhouse Gas Emissions (GGE) and their life cycle is a crucial research area for understanding the environmental impact of human activities and developing strategies for climate change mitigation(Gulcimen et al., 2021). The life cycle approach is a valuable tool for assessing GGE emissions across all stages of a process, product, or system, from raw material extraction to final disposal. This includes production, transportation, use, and disposal of goods and services. Life Cycle Assessment (LCA) involves collecting detailed data on material flows, energy, and emissions at each stage, enabling a comprehensive analysis of environmental impacts(Hausberger et al., 2023, Keiser et al., 2023).

Greenhouse Gas Emissions (GGE) are intrinsically linked to the modern transportation system, playing a significant role in global climate change. The transportation sector is a major source of GGE due to the predominant use of fossil fuels like gasoline and diesel, releasing carbon dioxide (CO2) and other pollutants into the atmosphere. The impact of GGE emissions from the transportation system is complex and encompasses a variety of transportation modes and related practices(Da Fonseca-Soares et al., 2022b) (Chipindula et al., 2021).

In the context of studying GGE emissions and their life cycle, it's common to assess different alternatives to identify the most sustainable options. For example, when comparing different transportation systems, one can analyze not only the direct emissions from vehicles but also emissions associated with the manufacturing, maintenance, and operation of infrastructure such as roads, rails, or airports (Ramos da Silva et al., 2023). Furthermore, life cycle analysis can highlight opportunities to reduce emissions at different stages of the cycle. This might involve improving energy efficiency in vehicle production, using more sustainable materials, promoting public transportation, expanding bike lane networks, and implementing policies that encourage the adoption of cleaner technologies (Leichter et al., 2021).

In this scenario, railways play a crucial role as a more sustainable transportation alternative, contributing to the reduction of GGE emissions and the development of more efficient and environmentally responsible transportation systems. The life cycle analysis of Greenhouse Gas Emissions (GGE) in the railway context is an approach that enables a complete understanding of the environmental impact of railway operations, from the design and construction of infrastructures to the operation and maintenance of railway systems. This comprehensive methodology is essential for accurately and holistically assessing emissions associated with rail transportation and identifying mitigation opportunities (de Bortoli et al., 2020, Merchan et al., 2020).

Furthermore, this approach allows for identifying critical emission points throughout the life cycle where interventions can be made to reduce overall emissions. This might involve adopting cleaner technologies, improving energy efficiency, changing consumption patterns, or implementing more sustainable practices (Gebler et al., 2020, Kaewunruen et al., 2020). Greenhouse Gas Emissions from the transportation system, including railways, pose one of the major challenges in addressing climate change. The adoption of cleaner technologies, promotion of sustainable transportation alternatives, and smart urban planning are essential to mitigate the environmental impacts of the transportation sector and contribute to a more sustainable future(Trevisan and Bordignon, 2020).

In this context, this research provides a comprehensive approach to the study of investigation focusing on the analysis and measurement of greenhouse gas emissions in rail transportation. By doing so, it assists researchers in gaining a thorough understanding of the current state of research in this area and the persistent issues. Furthermore, it seeks to provide guidelines and recommendations for further in-depth investigation in this field in the future. Additionally, this research aims to address the following questions regarding studies of greenhouse gas emissions in the global railway system:

Q1. What are the carbon emission characteristics of railways?

Q2. What editorial trends exist in relation to studies of greenhouse gas emissions in railway systems?

Q3. What calculation models are used in research on carbon emissions from rail transportation?

Q4. What are the complexities and limitations of measuring carbon emissions from transportation?

Q5. What research trends exist regarding the mitigation of greenhouse gas emissions in the railway system?

2. Carbon Emission Characteristics of Railways

As carbon emission characteristics in the railway context are of great importance when considering the environmental footprint of this mode of transportation. Carbon emissions, primarily in the form of greenhouse gases (GHGs), play a significant role in global climate change. Railways, as a mode of transportation, possess distinct characteristics that influence their carbon emissions and contribution to global warming (Jasti and Vinayaka Ram, 2021).

One of the distinctive features of railways is their energy efficiency compared to other modes of transportation, such as roads and airplanes. Generally, rail transportation is considered one of the most efficient and environmentally friendly modes in terms of carbon emissions. Trains have a high capacity for carrying freight and passengers, resulting in relatively higher energy efficiency per unit of cargo or passenger transported (Chen, 2022). Furthermore, electrification of railways, when electricity is sourced from renewable sources, can further reduce local carbon emissions. This leads to railway transportation emitting less compared to other modes(Aminzadegan et al., 2022).

Road transportation, which includes cars, trucks, and buses, generally has a higher carbon footprint compared to the railway system. This is partly due to the lower energy efficiency of these vehicles, especially when carrying smaller loads or fewer passengers (Liljenstrom et al., 2019). Internal combustion engines commonly used in road vehicles are less efficient in terms of energy conversion while in motion, resulting in higher fuel consumption and consequently higher GHG emissions (Makarchuk and Saxe, 2019). Moreover, a study on the impact of cargo modal transfer policy on carbon emissions in China concluded that road transportation is the most polluting mode among various transportation modes, while rail transportation has lower carbon emissions (Chen et al., 2020).

However, buses don't always emit more GHGs than trains. In the case of the Sheppard subway line in Toronto, Canada, it highlights the complexity of analyzing greenhouse gas emissions (GHGs) in transportation systems and how results can vary over time. In this specific example, the subway line initially produced more GHGs per passenger-kilometer than the buses it replaced during the first six years of operation. However, after this period, the carbon reduction benefits of the subway line began to become more evident (Saxe et al., 2017).

This case underscores the importance of considering the evolution over time when assessing the environmental benefits of transportation projects. While the initial impact may not be immediately positive, the potential for significant reductions in GHG emissions can materialize as the system matures and becomes more efficient. This also highlights the need for a comprehensive and long-term approach when planning and evaluating transportation projects with the goal of mitigating climate change and reducing carbon emissions.

ir transportation, on the other hand, is known to have a significantly higher carbon footprint compared to rail and road systems. Airplanes consume large amounts of fuel during flight, resulting in substantial GHG emissions per passenger or cargo transported. Additionally, GHG emissions from aviation occur at higher altitudes, which can have an amplified impact on the climate. Although there have been advances in improving the efficiency of jet engines and the adoption of biofuels, air transport is still considered one of the most polluting modes in terms of carbon emissions (Trevisan and Bordignon, 2020, Kim et al., 2023).

Comparing carbon emissions between rail, road, and air systems underscores the importance of energy efficiency and the type of fuel used. The railway system stands out for being more efficient and often cleaner due to electrification. The road system generally occupies an intermediate position in terms of emissions, while the air system is recognized for its relatively high emissions. This comparison emphasizes the need to consider environmental sustainability when choosing a mode of transportation and highlights the importance of policies and innovations aimed at reducing GHG emissions across all modes of transportation(Aminzadegan et al., 2022). However, even though railways are generally considered a more sustainable option in terms of carbon emissions compared to other modes of transportation, it is important to recognize that emissions can still occur, especially if the electricity used is not sourced from clean sources.

The electrification of railways in many regions contributes to carbon emission reduction. Electric trains directly eliminate emissions from the combustion of fossil fuels, making them a cleaner option in terms of local emissions. However, the carbon footprint of electrification depends on the energy matrix used to generate electricity. If electricity comes from renewable sources, carbon emissions associated with railway operation can be further reduced (Han et al., 2021, Sekasi and Martens, 2021).

The study analyzing the four typical urban railway lines (lines 6, 9, 10, and 15 of the subway) in Beijing in 2014 yielded important results regarding carbon emission reduction and the influence of various factors in this scenario. The results demonstrated the complex interconnection between urban rail transit, carbon emissions, and specific factors affecting these emissions (Chen et al., 2017).

The study showed that urban railway lines had a positive impact on carbon emission reduction in Beijing. This suggests that the implementation of these lines contributed to a more sustainable environment and the mitigation of greenhouse gas emissions. Carbon emissions from urban rail transit were strongly correlated with the carbon emission factor of the electricity used to power the system. This underscores the importance of the energy source behind rail transportation, with electrification and the use of clean energy sources being crucial to maximize environmental benefits(Chen et al., 2017).

The study also identified a correlation between carbon emissions and the proportion of passenger trips using modes of transportation prior to the opening of urban railway lines. This suggests that passenger adoption and switching to rail transportation had a direct impact on emissions reduction. The sensitivity analysis conducted in the study helped identify which factors significantly influenced carbon emissions. This is crucial to guide future planning decisions and public policies, aiming to optimize the environmental efficiency of urban railway lines (Chen et al., 2017).

Collectively, these findings highlight the importance of urban railway transportation as a more sustainable alternative to previous modes of transportation, contributing to carbon emission reduction in urban areas. Furthermore, they underscore the need for integrated approaches that consider not only the railway system itself but also influencing factors such as electricity sources and passenger behavior. This can inform transportation and energy policies aimed at continuous reduction of greenhouse gas emissions in urban areas.

An investigation in China identified railway electrification as a key means to reduce carbon emissions and optimize the transportation energy structure in the country. The results indicated that railway electrification using the current energy generation mix could reduce carbon emissions by 8.9%. However, utilizing a generation mix similar to that of the United Kingdom could help achieve a maximum reduction in carbon emissions of 65.4% (Xu et al., 2020).

A fundamental aspect highlighted by the research was the role of the energy generation mix in determining the effectiveness of railway electrification in reducing carbon emissions. The composition of energy sources used for electricity generation plays a crucial role, as cleaner sources like renewables result in lower emissions associated with the operation of electric trains. The study demonstrated that adopting an energy generation mix similar to that of the United Kingdom, which has a substantial proportion of renewable energy in its energy matrix, could lead to a much more significant reduction in carbon emissions in the Chinese railway system(Xu et al., 2020).

This research underscores the importance of considering not only the electrification technology itself but also the origin of the electricity used to power railway systems. It also demonstrates the potential for international cooperation, as experiences and best practices from other countries can be leveraged to maximize the benefits of railway electrification in terms of carbon emission reduction. In summary, the research highlights railway electrification as a promising strategy to achieve emission reduction goals and optimize the energy structure in transportation systems, with positive implications for the environment and the global climate (Xu et al., 2020).

Railway electrification is recognized as a crucial strategy for making transportation systems more sustainable and with a lower carbon footprint. By replacing diesel locomotives with electric trains powered by renewable or cleaner energy sources, it's possible to significantly reduce greenhouse gas emissions. This shift not only contributes to climate change mitigation but also improves air quality and reduces noise pollution in urban areas near railway lines (Lu et al., 2022).

It's worth noting that carbon emissions are also related to operational practices and proper maintenance of tracks and trains (Hu et al., 2021, Duraisamy et al., 2021, Zhu et al., 2021b). Improvements in fleet management, regular maintenance, and route optimization can result in enhanced efficiency, which in turn can reduce carbon emissions. Furthermore, challenges related to infrastructure, network modernization, and expansion can also influence carbon emissions in different railway systems.

Carbon emissions in the railway sector are influenced not only by the energy sources used to power the trains but are also intrinsically linked to operational practices and proper maintenance of railway infrastructure and trains. The efficiency and sustainability of the railway system depend on a combination of factors, ranging from daily operations management to preventive maintenance strategies (Sinha, 2021, Jasti and Vinayaka Ram, 2021).

Operational practices play a pivotal role in determining carbon emissions. For instance, optimizing train scheduling and operations can result in lower energy consumption and, therefore, reduced emissions. The adoption of regenerative braking strategies, which capture and reuse part of the kinetic energy during train deceleration, can contribute to energy efficiency and emission reduction(Rudin-Brown et al., 2019).

Moreover, proper maintenance of railway tracks and trains is crucial to minimize energy losses and ensure the efficient operation of the system. Well-maintained tracks reduce friction and allow smoother operation, which in turn reduces energy consumption. Similarly, regular maintenance of trains, including component cleaning and lubrication, ensures they operate efficiently, avoiding energy waste and unnecessary emissions (Wu et al., 2021, Yang et al., 2021, Bai et al., 2021, Wang and Lei, 2021).

Furthermore, innovative technologies such as more efficient propulsion systems and lightweight materials also play a role in reducing carbon emissions in the railway sector. Continuous research and development in these areas can contribute to improving energy efficiency and reducing emissions associated with railway operation(Guo et al., 2009).

The carbon emission characteristics of railways are shaped by their energy efficiency, electrification, and operational practices. While it offers advantages in terms of carbon emission reduction compared to other modes of transportation, it's essential to consider the energy source and implement sustainable practices to maximize its environmental benefits. Understanding these characteristics is crucial for guiding efforts in carbon emission mitigation in the railway sector and contributing to the sustainability of the transportation system as a whole(Fageda, 2021).

In another recent study, an estimation of carbon emissions generated by the daily operation of the metro system was conducted. The results obtained from this analysis allowed for the calculation of carbon emissions per kilometer traveled or per passenger trip. This approach provided a solid theoretical basis for the government to consider implementing policies such as carbon taxes for citizens and the creation of a carbon offset mechanism(Yu et al., 2020).

By determining the carbon emissions associated with the day-to-day operation of the metro system, this study contributed to understanding the specific contributions of this mode of transportation to greenhouse gas emissions. Quantifying emissions per kilometer or per passenger trip offered valuable information to underpin environmental and economic policy formulation(Yu et al., 2020).

Particularly, the study results served as a foundation for considering measures such as carbon taxes. This strategy aims to incentivize carbon emission reduction by imposing a tax on greenhouse gas emissions. By establishing such a tax, the government seeks not only to promote environmental awareness but also to create a financial incentive for adopting low-emission alternatives, such as the use of public transportation like the metro, over more polluting modes (Yu et al., 2020).

Furthermore, the study paved the way for the implementation of a carbon offset mechanism. This refers to an approach in which individuals or organizations can invest in carbon mitigation projects, such as reforestation or clean technologies, to offset their own carbon emissions. This approach plays a significant role in combating climate change by encouraging actions that result in the neutralization or net reduction of greenhouse gas emissions(Yu et al., 2020).

The study conducted by Yu (Yu et al., 2020) played a pivotal role in providing a solid theoretical foundation for policy formulation such as carbon taxes and the implementation of a carbon offset mechanism. These strategies are crucial for promoting environmental awareness, encouraging the adoption of sustainable modes of transportation, and contributing to the mitigation of greenhouse gas emissions.

In summary, railways stand out as a mode of transportation with favorable carbon emission characteristics due to their energy efficiency, electrification options, and potential for ongoing emissions reduction through sustainable operational practices. These aspects make railways an attractive alternative for mitigating GHG emissions in the transportation sector and contributing to the pursuit of more sustainable solutions in addressing climate change.

3. Trends in Greenhouse Gas Emission Studies in Railway Systems

The trends in studies concerning greenhouse gas emissions (GEE) in railway systems align with the global need to address climate change. The pursuit of more sustainable and efficient solutions in the railway transport sector continues to evolve, reflecting the growing importance of mitigating emissions and promoting greener and more responsible transportation. Studies are increasingly focused on understanding and reducing GEE emissions in railway systems as part of global efforts to combat climate change. There is a growing awareness of the importance of cleaner and more efficient transportation systems.

There is a rising interest in comparing GEE emissions from railway systems with other modes of transportation, such as highways and aviation. This helps identify the advantages and disadvantages of each mode and informs sustainable transportation policies(Aminzadegan et al., 2022) (Chen et al., 2020).

The electrification of railways, along with the use of renewable energy sources, is gaining prominence. Studies are exploring how electrification can reduce GEE emissions and how the incorporation of clean energy can further enhance environmental efficiency (Sekasi and Martens, 2021). Research is investigating innovative technologies, such as energy regeneration systems, aerodynamic improvements, and operational optimization, that can contribute to the reduction of GEE emissions in railway systems(Yang et al., 2021).

Public policies related to climate change and sustainability have influenced studies on GEE emissions in railway systems. Researchers are assessing how policies incentivizing electrification, infrastructure investment, and regulations can impact emissions (Chen, 2022). Studies are using modeling to project future GEE emissions in railway systems based on different scenarios of growth, electrification, and technology adoption. This helps identify emissions reduction pathways. The analysis of GEE emissions in railway systems is increasingly considering regional and global specificities, including differences in energy matrices, population density, travel patterns, and government policies(Zhu et al., 2021c).

4. Calculation model used in the research on carbon emissions in railway transportation.

There are two main approaches to calculate carbon emissions in urban railway transportation. The first is based on energy consumption at the end use and associated carbon emission factors. The second involves direct measurement of CO2 emission factors, considering travel distance and the mode of transportation used.

In the first method, carbon emissions are calculated by considering the amount of energy consumed by the railway system during its operation. This includes electricity consumption for moving trains, station lighting, air conditioning systems, among others. The consumed energy is then related to carbon emission factors, which indicate the amount of carbon dioxide released into the atmosphere per unit of energy consumed. This approach considers the carbon footprint of the entire system and is often used in life cycle analysis studies (Ramos da Silva et al., 2023, Da Fonseca-Soares et al., 2023).

In the second method, direct measurement of CO2 emission factors is carried out based on travel distance and the mode of transportation. This involves collecting data about the trips taken, including the distance traveled and the type of transportation used, such as subway, train, or tram. From this data, CO2 emissions associated with each mode of transportation are calculated, taking into account the specific operational characteristics of each. This approach is more direct and can provide immediate insights into carbon emissions in terms of distance traveled(Wei and Pan, 2017).

Both approaches are valuable for assessing carbon emissions in urban railway transit and are often used in comparative studies between different modes of transportation and policy analyses for emission reduction. The choice between these methods depends on data availability, study objectives, and the desired accuracy in estimating carbon emissions.

Table 01 summarizes and analyzes some of the research work on rail GHG emissions analysis and measurement in the literature.

Table 01. GHG emissions measurement model of rail in literature

Country	City	Research boundary	Summary	Reference
United States	Texas	LCA	Study of greenhouse gas emissions from metro construction, operation, and maintenance	(Chipindula et al., 2021)
Brazil	Pernambuco	Operation and maintenance	Study of greenhouse gas emissions from metro operation and maintenance	(Da Fonseca-Soares et al., 2023)
korea	Gwangju	Construction and building	Study of greenhouse gas emissions from railway construction	(Lee et al., 2020)
China	shanghai	LCA	Study of greenhouse gas emissions from metro construction, operation, and maintenance	(Li et al., 2018b)
Áustria	Vienna	LCA	Ignoring carbon emission from maintenance, dismantling, and recycling phases	(Gassner et al., 2018)
United States	Los Angeles	LCA	Two different LCA frameworks are used	(Houston et al., 2016)
United States	Phoenix	LCA	Developed an integrated transportation and land use LCA framework	(Kimball et al., 2013)
China	Beijing	Construction and building	A quota-based GHG emissions quantification model for metro station construction is proposed	(Liu et al., 2018)
Canada	Toronto	Operation and maintenance	Study of GHG emissions from the construction and reconstruction of the Spadina streetcar route	(Makarchuk and Saxe, 2019)
United Kingdom	London	Operation and maintenance	Analyzed the impact of changes in passenger travel behavior on GHG emissions from metro	(Ball et al., 2021)
United States	New Jersey	Construction and building	Different material inputs were evaluated during the construction of the railroad project	(Hanson et al., 2016)
Italy	Rome	LCA	The use of data sourced from metro operators reduces the uncertainty of the results	(Del Pero et al., 2015)
Turkey	Kayseri	LCA	Integrating environmental, economic, and social factors with the LCA approach	(Gulcimen et al., 2021)
China	Beijing	Operation and maintenance	No carbon emission by default for power generation methods other than thermal power	(Kaewunruen et al., 2020)
Índia	Delhi	Operation and maintenance	The impact of transport mode shift due to the introduction of the metro on carbon emission is considered	(Gopal and Shin, 2019)
China	Baoji	Operation and maintenance	Developed a passenger demand-based carbon emission model	(Zhang et al., 2020)

4.1 Lifecycle-based greenhouse gas emission calculation

Most studies that utilize the approach based on final energy consumption and carbon emission factors focus on measuring carbon emissions during the operational phase of urban railway systems. In this method, the calculation of greenhouse gas (GHG) emissions is conducted by multiplying the electric energy consumption of urban railway systems by the associated carbon emission factor for electricity. This approach takes into account the total electric energy consumption necessary to operate the railway system, including train movement, lighting systems, ventilation, and other components. The energy consumption is then multiplied by the carbon emission factor of electricity, which represents the amount of CO_2 released into the atmosphere per unit of consumed electric energy. This multiplication provides an estimate of the carbon emissions associated with the operation of the railway system.

Life Cycle Assessment (LCA) in the railway system is a comprehensive approach for evaluating the emission of GHGs throughout all phases of the life cycle of a railway system, from raw material extraction to final disposal. LCA considers the environmental aspects related to material production, construction, operation, maintenance, and eventual disposal of a railway system(Ramos da Silva et al., 2023). LCA is a valuable tool for quantifying and evaluating GHG emissions and other environmental impacts associated with the railway system. It enables an objective comparison among different design, operation, and maintenance alternatives, identifying key areas where improvements can be made to reduce environmental impact (Leichter et al., 2021).

The study conducted on the Pernambuco metro had as its primary goal to analyze greenhouse gas (GHG) emissions associated with the operation and maintenance of this transportation system. The study found that the total GHG emissions over the entire life cycle of the Pernambuco railway system, including its construction phase, amounted to 6,170.54 metric tons of CO_2 equivalent (tCO_2e). This value represents the overall impact of GHG emissions from the beginning of construction to the operation and maintenance of the system. Based on an estimated system lifespan of 50 years, the study projected that future emissions would be equivalent to 308,550 tCO_2e. This highlights the relevance of considering the complete life cycle of a railway system when assessing its environmental impact, as emissions are not limited solely to the operational phase but also include the construction phase and potential maintenance over the years(Da Fonseca-Soares et al., 2023).

These results are crucial for understanding the role of GHG emissions in the sustainability of the railway system in Pernambuco and for guiding potential mitigation strategies. The study provides valuable information for making informed decisions to reduce emissions over time, whether through improvements in energy efficiency, adoption of cleaner energy sources, or implementation of more sustainable maintenance practices. This research contributes to raising awareness about the environmental impact of railway transportation and provides a starting point for the implementation of measures aimed at making the system more environmentally responsible and contributing to climate change reduction.

A study conducted in China employed the Life Cycle Assessment (LCA) methodology to define the life cycle system of the Shanghai Metro, along with compiling observed real-world data on resource inputs and generated emissions. The study also conducted a comparative analysis of Greenhouse Gas (GHG) emissions from various urban railway systems worldwide (Li et al., 2018b).

The results indicate that the total GHG emissions over the life cycle, considering the complete construction extension of the Shanghai Metro with a 50-year lifespan, amount to 109,642.81 metric tons of CO2 equivalent. Material production, material transportation, on-site construction, operation, and maintenance were responsible for approximately 4.1%, less than 0.1%, 0.4%, 92.1%, and 3.4% of the total emissions, respectively. While GHG emissions per passenger-kilometer traveled of the Shanghai Metro present global competitiveness, the study points out that there is significant energy-saving potential during the operational phase, especially in railway stations with more elaborate designs (Li et al., 2018b).

The preliminary conclusions of this study provide an understanding of the potential emissions reduction in urban railway transit systems, contributing to emissions reduction goals in China. Furthermore, the results can serve as a valuable source of information and data for future Life Cycle Assessments (LCAs), aiding in the formulation of emissions mitigation strategies in similar transportation systems.

A study in Korea employed LCA to quantify Greenhouse Gas Emissions (GEE) originating from construction modules encompassing various stages such as earthwork, civil engineering activities (including tunnel, viaduct, and bridge construction), railways, passenger stations, and power transmission and telecommunication systems for all HSR lines. Additionally, the study identified the primary activity within each module. The study also analyzed the interdependence between GEE emissions and civil engineering works. This study provided an estimate of GEE emissions during the construction phase of a high-speed railway (HSR) infrastructure connecting Osong to Gwangju, South Korea, inaugurated in 2015. Total GEE emissions reached approximately 3.7 million metric tons of carbon dioxide equivalent (MtCO2eq.), with about 92% originating from material use, an indirect emission source (Lee et al., 2020).

The study conducted in Belgium offered a comprehensive assessment of the environmental impact of freight railway transportation in the country, using the Life Cycle Assessment (LCA) methodology. This study analyzed various aspects related to railway transportation, including different types of trains and energy sources used for traction, in order to understand the environmental impact associated with each of these options. The LCA adopted in this study considered not only direct processes related to transportation activities, such as energy consumption and direct emissions, but also other factors involved in the railway system, such as energy production, manufacturing of railway equipment, and the necessary infrastructure for operation. The study divided the freight railway transportation system into three distinct subsystems: operation, railway equipment, and infrastructure (Merchan et al., 2020).

The results indicated that electric trains exhibit superior environmental performance compared to diesel trains in Belgium. The use of electric trains, driven by the Belgian electricity supply mix of 2012, led to a significant reduction in climate change-related environmental impact, reaching a reduction of 26%. Furthermore, the study suggested that increasing the use of electric trains in the future will have a significant impact on the environmental and energy aspects of freight railway transportation. The growing adoption of sustainable electric energy for the operation of electric trains can lead to a more efficient and environmentally friendly freight railway system (Merchan et al., 2020).

The study conducted in the Houston-Dallas corridor (I-45) employed a Life Cycle Assessment (LCA) approach to predict and evaluate net changes in environmental impact associated with the potential development of a high-speed railway (HSR) system along this corridor. The primary objective was to estimate the environmental impact, particularly in terms of carbon dioxide (CO2) emissions and Greenhouse Gas (GEE) emissions per vehicle/passenger-kilometer traveled (V/PKT) over the entire life cycle of the system. The study adopted a comprehensive approach, considering various phases of the railway system's life cycle, including material extraction and processing, infrastructure construction, vehicle manufacturing, system operation, and end-of-life. The Ecoinvent 3.4 inventory database was used as a data source for the analysis (Chipindula et al., 2021).

The study's results highlighted some important conclusions. Vehicle operation and maintenance were identified as the primary contributor to the total potential global warming, accounting for about 93% of the life cycle Greenhouse Gas (GEE) emissions. Regarding the infrastructure component, the phase of material extraction and processing was identified as the major contributor, representing approximately 56.76% of GEE emissions, with around 23.75 kgCO2eq/VKT. In comparison, the study revealed that various emissions associated with the high-speed railway system throughout its life cycle, except for particulate matter (PM), are significantly lower than those emitted by passenger cars(Chipindula et al., 2021)

Another important study conducted a comprehensive assessment of the life cycle sustainability of a light rail transportation system in Kayseri, Turkey. The assessment incorporated environmental, economic, and social aspects to provide a holistic understanding of the system's sustainable performance. For the environmental assessment, a Life Cycle Assessment (LCA) approach was employed using SimaPro 8.4.1 software, in accordance with ISO 14040 and 14044 standards. Nine categories of environmental impact were considered to assess the environmental performance of the light rail transportation system, with a functional unit of 1 passenger-kilometer. The results indicated that the global warming potential and abiotic depletion potential of the light rail transportation system per passenger-kilometer were 2.4E-02 kg CO2 eq. and 2.7E-01 MJ, respectively, considering a 50-year lifespan (Gulcimen et al., 2021)

Economic assessment was conducted through life cycle costing, using the functional unit of 1 US dollar per 1 passenger-kilometer. The total life cycle cost of the light rail transportation system was calculated as 0.046 USD per 1 passenger-kilometer. The results highlighted that energy cost was the primary contributor to the total life cycle cost, accounting for about 92% of the total cost. Regarding the social performance assessment, the study identified that the light rail transportation industry demonstrates good performance in terms of benefits for society, the local community, and workers. However, social performance in relation to consumers was evaluated as weaker due to a less effective feedback mechanism (Gulcimen et al., 2021)

In summary, Life Cycle Assessment (LCA) studies of Greenhouse Gas Emissions (GEE) in railway systems are essential for promoting the transition to more sustainable transportation systems, enabling the adoption of informed strategies to reduce environmental impacts, optimize efficiency, and promote environmentally friendly practices.

4.2 Calculation of carbon emission factors based on distance traveled and mode of transportation.

The calculation of carbon emission factors based on distance traveled and mode of transportation is a fundamental approach to estimating greenhouse gas (GHG) emissions associated with transportation activities. This methodology involves determining the amount of CO2 equivalent emitted per unit of distance traveled in different modes of transportation, enabling a direct assessment of the environmental impact of these activities(Soni and Chandel, 2018).

First and foremost, the distance traveled is a key parameter in this calculation, representing the length of the journey undertaken. This distance can vary from short urban trips to longer routes between cities or regions. Next, the mode of transportation used is also a crucial factor, as different transportation modes have different energy efficiencies and consequently different GHG emissions. Modes such as gasoline, diesel, electric vehicles, or rail and road public transport have different emission pattern(Lee et al., 2020).

Carbon emission factors are expressed in terms of the mass of CO2 equivalent emitted per unit of distance, such as kilometers traveled. These factors can be obtained through measurement data, fuel consumption analyses, direct emissions, or life cycle modeling, depending on the desired accuracy(Shao et al., 2005).

The combination of these elements - distance traveled and mode of transportation - results in a quantitative estimate of GHG emissions related to transportation activities. These calculations are vital for understanding the environmental impact of different mobility options, aiding in the formulation of sustainable policies, smart urban planning, and individual transportation choices that contribute to carbon emissions reduction and climate change mitigation(Aminzadegan et al., 2022, Steffen et al., 2015).

In a study in Baoji, the assessment of the environmental impact of urban rail transportation was addressed, focusing on carbon emissions reduction. The study uses the prediction of passenger demand in the city of Baoji as a basis to analyze the environmental benefits of the rail transportation system. Scenarios of travel are outlined considering the use of rail transportation and its absence, taking into account the extent of demand generated by different modes of transportation. Carbon emissions from trips are calculated by multiplying the per capita emission of each mode of transportation by the total number of passengers on the target routes. The study highlights the importance of low-carbon urban rail transportation as a sustainable alternative to reduce carbon emissions related to urban transport (Zhang et al., 2020).

A study on low-carbon in Beijing discussed the creation and use of software designed to calculate energy consumption and greenhouse gas emissions in the context of transportation. This software is developed based on research and principles of low-carbon transportation in Beijing, with the main objective of providing a comprehensive tool to assess the environmental impact of various modes of transportation (Shen et al., 2013).

The process of software development is outlined, including the incorporation of data related to vehicle fleets, energy sources, distances traveled, and other relevant factors. The authors emphasize the flexibility of the software, allowing customization based on specific urban contexts, transportation systems, and policy objectives. It also considers real-time data, increasing its applicability to assess dynamic transportation scenarios. The application of the software is demonstrated through case studies and simulations, focusing on various modes of transportation in the metropolitan area of Beijing. These studies illustrate how the tool can assess the impact of different transportation policies and interventions, providing insights into emission reduction and energy efficiency improvements. This can guide urban planners, policymakers, and researchers in identifying strategies to promote sustainable and low-carbon transportation systems (Shen et al., 2013).

Furthermore, the article discusses the potential of the developed software to contribute to broader urban sustainability goals, such as reducing traffic congestion, improving air quality, and enhancing overall quality of life. It underscores the importance of integrating energy consumption and emissions analysis into urban planning and transportation management (Shen et al., 2013).

These studies are important for understanding the environmental impact of the operational phase of urban rail systems and for assessing GHG emissions over time. However, it is crucial to consider that this approach may not capture all emissions associated with the complete life cycle of the system, such as the manufacturing, construction, and maintenance of rail infrastructures. Therefore, a comprehensive analysis of carbon emissions may require the combination of different approaches and the consideration of all stages of the life cycle.

5. A complexity and limitation of carbon emissions measurement in transportation.

The life cycle assessment (LCA) is an essential approach to understanding the environmental impact of systems and products throughout all stages of their life cycle, from raw material extraction to disposal. However, the full application of LCA to the railway system may face significant challenges due to the lack of complete and detailed data, especially in the construction stage of railways(Olugbenga et al., 2019).

The lack of comprehensive data on the construction of older railways can create a gap in the life cycle analysis, particularly when it comes to calculating greenhouse gas emissions (GHG) associated with the construction phase. Many studies that aim to assess the environmental impact of railways might focus on operational and maintenance phases where data is more accessible. The absence of detailed construction data can hinder the accurate estimation of GHG emissions in the construction stage, which, in turn, can lead to an incomplete understanding of the overall impact of railways on climate change. This can be an obstacle to obtaining a holistic view of the life cycle and conducting accurate comparisons between different modes of transportation or sustainability interventions (Ingrao et al., 2021).

To address this limitation, researchers can adopt strategies such as using indirect data, modeling, and simulation to estimate GHG emissions in the construction phase. Furthermore, it's important to acknowledge that LCA is not limited solely to the construction phase; operational and maintenance phases also play a crucial role in evaluating the environmental impact of railway systems. Although the lack of comprehensive construction data may present a challenge, it's essential to consider that LCA can still provide valuable insights into the sustainability of railways throughout their lifespan. Focusing on stages where data is available, along with creative approaches to fill information gaps, can enable researchers to gain a more complete understanding of the environmental impact of railways, even when construction data is limited (Merchan et al., 2020).

In the research conducted on the railway system in Pernambuco, the assessment of greenhouse gas emissions (GHG) exclusively focused on the maintenance and operational phases. This is due to the fact that, due to the age of the railway, construction-related data was no longer available. As a result, the life cycle of GHG emissions ends up being incomplete in this aspect (Da Fonseca-Soares et al., 2023). Previous studies, such as those addressing gas emissions in the Shanghai metro, indicate that the portion of GHG emissions associated with the construction phase is not as significant compared to operational and maintenance phases. In many cases, this portion accounts for only about 5% of the entire GHG emissions cycle of the system. Therefore, while the Life Cycle Assessment (LCA) approach may not be fully comprehensive due to the lack of construction data, this limitation does not seem to have a substantial impact on the final results (Li et al., 2018b).

This suggests that while the lack of construction data may create a limitation in the comprehensive life cycle analysis of GHG emissions, the focus on operational and maintenance phases, which generally have a larger contribution to the total emissions, still offers valuable insights into the sustainability of the railway system. Therefore, even though the lack of comprehensive construction data may influence the LCA approach, its impact on the final results is relatively limited, especially when considering the proportion of emissions from different life cycle phases.

The quality and comprehensiveness of data used in calculating greenhouse gas emissions (GHG) in the railway system play a fundamental role in the reliability of results obtained by assessment models. The accuracy of estimates depends directly on the availability of reliable and detailed data sources related to the railway transport sector (Manzo et al., 2018). Collecting reliable data is essential to ensure that the calculation model accurately reflects the real conditions of the railway system. Detailed, up-to-date, and comprehensive statistics are necessary to provide a complete view of railway operations, including factors such as distance traveled, type of locomotive used, energy consumption, and operational characteristics. Otherwise, estimates can be inaccurate and underestimate or overestimate actual emissions(Merchan et al., 2020, Boschiero et al., 2019, Olugbenga et al., 2019).

Furthermore, it's crucial for data sources to be transparent and verifiable. The lack of transparency or unavailability of data used in the calculation can raise questions about the credibility of the results obtained. Obtaining data directly from responsible railway authorities or trustworthy research institutions can enhance the reliability of estimates. Another challenge is ensuring the consistency and updating of data over time. The railway transport sector is subject to changes, such as the introduction of more efficient technologies or the expansion of networks. Therefore, calculation models should be periodically reviewed and adjusted based on updated data to maintain the accuracy of estimates(Lee et al., 2020).

In a study conducted in China, which presents a comprehensive analysis of the transportation system and evaluates the effectiveness of current strategies aimed at sustainable transportation development, the authors use modeling techniques to assess various transportation scenarios. These scenarios consider factors such as modal choice, infrastructure development, and policy interventions. By simulating different strategies, they analyze their potential impacts on energy consumption, emission reduction, and overall transportation efficiency.

In the study conducted in China, significant findings related to oil consumption in the Chinese national transportation system were identified. They observed that oil consumption in the national transportation system accounted for 57% of the country's total oil consumption, a much higher proportion compared to the official statistics of 38%. This phenomenon was mainly attributed to the discrepancy between the Chinese energy statistics system and international standards. A relevant explanation for this discrepancy is related to the differences in data collection and calculation methods adopted by the Chinese energy statistics system compared to international standards. The variation in energy accounting systems can result in substantial differences in reported numbers of oil consumption in the transportation sector, which, in turn, affects the accurate understanding of this sector's contribution to total energy consumption and greenhouse gas emissions (Liu et al., 2013).

In the computational models used to estimate carbon emissions, many of these computational models have limitations in terms of dynamism and adaptability, as many components related to carbon emissions are defined statically. This characteristic can result in inaccuracies in emission calculations over time and in different contexts. Computational models used to estimate emissions should be developed with more dynamism and flexibility, allowing fluctuations in the transportation system over time to be captured more accurately in order to better reflect the operational reality of the transportation system (de Bortoli and Christoforou, 2020).

6. Trends in Research for Greenhouse Gas Emissions Mitigation in the Railway System

As trends in mitigation research of greenhouse gas emissions (GHG) in the railway system are evolving towards increasingly comprehensive and innovative approaches. As awareness of climate change and the importance of reducing GHG emissions grows, researchers are exploring a variety of areas and strategies to make the railway system more sustainable..

A significant trend is the transition to electrified railway systems or other systems with more sustainable fuels, reducing dependence on fossil fuels. This involves adopting renewable energy sources, such as electricity from wind, solar, hydro, or fuels like hydrogen and biodiesel to power trains. Shifting to a more sustainable fuel helps reduce GHG emissions by eliminating direct emissions from trains and optimizing energy efficiency (Xu et al., 2022).

A study in the railway system of northeastern Brazil addressed the application of solar photovoltaic systems on light rail vehicles (LRVs). The study explored the feasibility and benefits of incorporating solar technology to assist in the electric power supply of LRVs. The research considers the scenario of sustainable public transportation and the potential advantages of solar energy generation to reduce dependence on conventional sources and mitigate GHG emissions (Carneiro and Soares, 2020).

Another energy efficiency study presented a strategy to optimize water and energy use in public buildings, using a Brazilian railway company as a case study. The study addresses the importance of resource efficiency in public facilities, considering both cost reduction and environmental benefits. The research details the approach taken, including the implementation of measures such as rainwater harvesting, the installation of water-saving devices, and the use of renewable energy systems. The specific case study in the Brazilian railway company demonstrates the results obtained from the implementation of these measures, both in terms of financial savings and the reduction of natural resource consumption and GHG emissions (Carneiro et al., 2022).

Studies on the use of hydrogen in trains have gained prominence due to the search for cleaner and more sustainable transportation solutions. Hydrogen is considered a promising energy source for trains, as its combustion or conversion into electricity through fuel cells produces only water as a byproduct, eliminating pollutant emissions and GHGs. Overall, studies on hydrogen use in trains aim to provide comprehensive information on the technical, environmental, and economic feasibility of this energy alternative, contributing to informed decision-making by transport authorities and promoting the transition to more sustainable railway systems (Xu et al., 2022).

A study on Urban Light Hydrogen-Powered Rail explores the modeling, analysis, and practical implementation of an urban light rail powered by hydrogen fuel cells. The study focuses on exploring the feasibility and potential benefits of using hydrogen as an alternative energy source for urban rail transport. The study discusses various scenarios, considering different methods and hydrogen production technologies. This includes assessing emissions throughout the lifecycle and energy consumption of the entire system, from hydrogen production to train operation. The authors also consider the economic viability of implementing such a system, taking into account factors such as initial investment costs, operational expenses, and potential benefits in terms of reduced emissions and energy efficiency (Ciancetta et al., 2019).

In conclusion, the article presents a comprehensive analysis of implementing a light urban hydrogen-powered rail system. By addressing technical, economic, and environmental aspects, it provides valuable insights into the feasibility and potential benefits of adopting this system. The study's modeling, analysis, and practical considerations contribute to advancing sustainable transportation solutions and encourage further research and development in the field of hydrogen fuel cell technology for urban rail systems (Ciancetta et al., 2019).

Practical implementation is a crucial aspect as it aims to bridge the gap between theoretical analysis and real-world application. Exploring the technical challenges associated with integrating hydrogen fuel cells into existing rail systems, ensuring safety, reliability, and efficiency. Discussing potential barriers and regulatory considerations that need to be addressed for successful implementation is important for the evolution of sustainable railway transportation. The potential benefits of hydrogen rail systems, including reduced greenhouse gas emissions, improved air quality, and reduced dependence on fossil fuels, are discussed.(Ciancetta et al., 2019, Ibrahim and Ramesh, 2013).

Another significant research involving hydrogen in the railway system addresses the use of dual-fuel diesel engines operating with diesel injection and the introduction of fumigants such as hydrogen, gasoline, and ethanol. The main objective is to investigate how different diesel injection timing affects efficiency and emissions during multi-fuel combustion. The results show how varying the timing of diesel injection influences combustion efficiency, heat release rate, and emissions. The findings can offer valuable insights for optimizing the operation of dual-fuel engines, contributing to the reduction of pollutant emissions and the search for cleaner and more efficient alternatives in the transportation sector(Fang et al., 2014).

The use of biodiesel in the railway system is an approach aimed at partially or fully replacing conventional petroleum-derived diesel with a renewable and more sustainable fuel. Biodiesel is a biofuel produced from renewable sources such as vegetable oils, animal fats, or food waste through transesterification processes. Adopting biodiesel in the railway system aims to reduce pollutant emissions and contribute to climate change mitigation, as biodiesel tends to generate fewer carbon dioxide (CO2) emissions and other atmospheric pollutants compared to fossil diesel. Additionally, biodiesel is biodegradable and produces less particulate matter, contributing to improving air quality in urban areas(Kurczyński, 2021, Leichter et al., 2021, Rajeswari et al., 2021).

However, implementing biodiesel in the railway system also faces technical and logistical challenges. Ensuring that train engines are compatible with biodiesel blends is necessary, as biodiesel has different combustion properties compared to conventional diesel. Additionally, the availability and quality of biodiesel can vary, which can affect the efficiency of the railway system(Thongchai and Lim, 2018).

Ongoing studies and research are assessing the impacts of biodiesel use in the railway system, such as evaluating nitrogen oxide (NOx) and nitrogen dioxide (NO2) emissions during cold start of a diesel engine when fueled with different proportions of diesel and biodiesel blends. The main aim of the study is to investigate how biodiesel blends affect NO2 and NOx emissions during the cold start phase of a diesel engine. Cold start is a critical period in terms of emissions, as engine temperatures are low and combustion is not ideal, which can lead to increased pollutant emissions. The results indicate how different biodiesel blend ratios affect NO2 and NOx emissions, highlighting impacts during cold start. This can provide valuable insights for the automotive industry and environmental policy formulation, aiming to reduce pollutant emissions and develop cleaner and more efficient fuels(Zare et al., 2021).

Another biodiesel research investigates the spray behavior of a common rail diesel injector using a blend of biodiesel with 5% gasoline. The analysis provides information about the spray pattern and how different operational factors impact this process, contributing to a comprehensive understanding of the use of biofuel blends in diesel engines. The results offer insights into the angle, shape, and dispersion of spray droplets, considering different operating conditions such as injection pressure and flow velocity (Thongchai and Lim, 2020).

Researchers are also focusing on improving the energy efficiency of railway systems, such as designing lighter and more aerodynamic trains, energy regeneration systems during braking, and route optimization to reduce energy consumption(Kostrzewski and Melnik, 2021, Ma et al., 2021, Rong et al., 2021).

A study addresses computational simulation of the contact response between wheels and tracks in a straight rail scenario. The research focuses on analyzing the behavior of wheel-track contact, taking into consideration different variables such as material characteristics, component geometry, and applied forces. The study utilizes dynamic simulations to understand how forces, deformations, and pressure distribution occur during the contact between wheels and tracks. The simulation results provide valuable information about the distribution of forces and stresses at the contact point, allowing for a deeper understanding of the system's performance and dynamic behavior. This has significant implications for the design and maintenance of railway systems, contributing to operational optimization and the reduction of greenhouse gas emissions (Zhou et al., 2021).

In railway systems, real-time traffic management allows for monitoring and controlling train movement in real-time, identifying potential congestion, delays, or operational issues. This immediate responsiveness enables corrective measures to be adopted, such as adjusting train speed, optimizing stop schedules, and coordinating traffic flow, thus minimizing delays and improving service regularity. The integration of intelligent operation systems into railway systems offers a range of notable advantages. These systems can optimize energy efficiency by determining the best way to use available energy and intelligently managing power distribution. This is particularly valuable in electrified railway systems, where electrification is common, contributing to reduced energy consumption and pollutant emissions(Aydin et al., 2021) (Kostrzewski and Melnik, 2021).

Effective integration among different modes of transportation (rail, road, cycling, etc.) allows for a more holistic approach to transportation system planning, reducing overall emissions by promoting more sustainable options.

A study involving an inference model for passenger itineraries in congested urban rail networks employs data from ticketing and train schedule information to estimate the routes and itineraries followed by passengers in congested urban rail transportation systems. Through the analysis of ticketing data and train schedules, the proposed model allows for estimating the most frequently used passenger routes, identifying major traffic flows and congestion points. This information can be used to develop congestion mitigation strategies, such as train redistribution, schedule adjustments, or the implementation of measures to avoid bottlenecks at key stations. This contributes to improving passenger experience and optimizing operations during high-demand situations, aiding in greenhouse gas emissions reduction (Zhu et al., 2021c).

In summary, research trends in greenhouse gas emissions mitigation within the railway system reflect a comprehensive approach involving electrification, energy efficiency, multimodal integration, sustainable technologies, and environmentally friendly policies. These trends aim to make railway transportation a more sustainable option and contribute to reducing greenhouse gas emissions in the transportation sector as a whole.

7. Considerações finais

The approach of this research focuses on advancements in studies related to carbon emissions measurement in the railway transportation sector, providing a comprehensive analysis of existing research. Currently, there is maturity in analyses that seek to assess the potential reduction of carbon emissions in railway transportation, as well as in defining research scopes, utilizing measurement methods, and developing models. However, this maturity coexists with challenges posed by the inherent complexity of the railway environment, including electricity generation, urban rail expansion, system longevity, and interactions with other transportation modes in a multimodal context.

Within this complex scenario, ensuring the accuracy of carbon emissions measurements emerges as a critical aspect. Appropriate determination of carbon emission factors, judicious selection of measurement steps, and verification of the accuracy and validity of employed data are crucial aspects that need to be considered in future research. The application of Life Cycle Assessment (LCA) methodology in the context of railway emissions is explored, and several articles are used as examples to illustrate this process. Despite the progress made, unresolved issues still remain. For instance, even though the use of LCA has become more systematic and refined, many studies fail to encompass the entire railway life cycle, especially in the initial construction phase.

Measuring carbon emissions in urban railway transportation systems presents multiple challenges and considerations. The precision and comprehensiveness of the required data for these measurements often encounter obstacles, and the very definition of carbon emissions can be ambiguous, complicating the task of accurately and simultaneously measuring emissions from this urban transport.

In summary, despite notable advancements, this research underscores that the intrinsic complexity of the railway transport context and the need for accurate measurements remain significant challenges in carbon emissions investigations within this sector. The application of LCA methodology offers a valuable framework, but the absence of data in certain life cycle phases and the ambiguity in emission definitions represent challenges to overcome in achieving a thorough and accurate understanding of the environmental impact of railway transportation.

To guide future research, it is crucial to direct efforts towards several key areas to enhance the understanding and approach to carbon emissions within the urban railway transportation system:

Data Collection and Quality Enhancement: An essential focus should be to ensure the accuracy and comprehensiveness of data detection and collection necessary for analyzing carbon emissions in urban railway transportation systems. This requires improved data acquisition methods and a more rigorous approach to data verification and validation, to enhance the overall quality of estimations.

Implementation of Monitoring Systems: Establishing a digital system that tracks Greenhouse Gas (GHG) emissions throughout the entire life cycle of the railway transportation system is fundamental. This digital twin system can integrate data from various life cycle phases, offering a holistic model and facilitating visualization and monitoring of railway transportation GHG emission measurements.

Integration of Multimodal Transport Modes: Most current studies focus on isolated analysis of urban railway traffic, often separating it from multimodal transportation systems. Thus, it is crucial for research to advance towards a more comprehensive analysis, considering the integration of railway transportation with other transportation modes in integrated urban systems, which can more realistically reflect the dynamics of carbon emissions.

Directing research efforts according to the outlined points will lead to significant advancements in the understanding and measurement of carbon emissions in the urban railway transportation system. This will provide essential information for well-founded and effective public policy formulation, contributing to emission reduction, climate change mitigation, and the promotion of more sustainable transportation. This approach will also have a significant impact on improving the quality of life for future generations.


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CHAPTER 03

LIFE-CYCLE GREENHOUSE GAS (GHG) EMISSIONS CALCULATION METRO FOR URBAN RAIL TRANSIT SYSTEMS: THE CASE OF PERNAMBUCO

The results presented in this chapter were published in the journal *Applied Sciences* (ISSN: 2076-3417)
Journal Rank Europe: JCR 2.7; CiteScore 4,5 - Q2 (*Engineering, Multidisciplinary*)/Q1 (*General Engineering*)
Journal Rank Brazil: A3 (*Environmental Studies*) / A3 (*Engineering I*)

1. Introducion

According to the 2020 UN report, the world's population is growing at a rate of 1.1%, and at this rate, the organization projects that the world will have 8.5 billion inhabitants by the year 2030. With the increase in population comes the need for greater consumption of natural resources and, consequently, an increase in pollution caused by this consumption (Chen, 2022). Faced with this fact, humans understand the need to develop consumption methods that have lesser impacts on the environment. However, effective ways to reduce the damage caused by pollution are still lacking.

Humans are demanding more and more natural resources every day, and the increasing demand raises concerns about how the impact of their consumption affects emissions of greenhouse gases into the atmosphere and how the waste generated by their activities may be directly linked to climate change. With the growing population, the consumption of goods and services in large urban areas requires more resources in terms of energy and land (!!! INVALID CITATION !!! (2)). In the background of this huge population mobility, the global outbreak of the COVID-19 pandemic in 2020 prompted people to reconsider privates vehicles utilizing more polluting technologies and affecting health through affecting population mobility and local air pollution levels (Zhang et al., 2023).

Anthropogenic climate change is a widely discussed topic worldwide, leading to international agreements such as the Kyoto Protocol and the National Policy on Climate Change established via Law No. 12.187/2009, which commits Brazil to reducing greenhouse gas (GHG) emissions. The recent global pact at the 21st Conference of the Parties (COP21) of the United Nations Framework Convention on Climate Change (UNFCCC) in Paris aims to strengthen the world's response to the threat of climate change and enhance countries' capacity to deal with the impacts of these changes (Costa et al., 2021).

The need to improve energetic efficiencies and to reduce pollution caused by transportation have gained importance because decarbonization has been identified as a crucial worldwide concern. The transport sector, being the largest producer of greenhouse gases (GHGs) in many countries, is recognized as a key factor in achieving climate mitigation targets (Aminzadegan et al., 2022, de Bortoli et al., 2020).

These climate change discussions in recent years have raised concerns among governments, the population, and scientists worldwide, emphasizing the need for action. Climate change may be related to increased concentrations of GHGs, primarily carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), hydrofluorocarbons (HFCs), perfluorocarbons

(PFCs), and sulfur hexafluoride (SF6) (Boschiero et al., 2019), although other gases also have this property.

In addition, the transport sector is also responsible for the emission of local pollutants such as NOx, CO, and particulate matter (PM). Global and local pollution issues are mainly due to the diffusion of diesel internal combustion engine powertrains in heavy-duty segments. Then, to understand which powertrain and fuel technologies are most capable of shrinking the carbon footprint of transport—and not only the emissions from the tailpipes, but also from fuel and electricity production and vehicle manufacturing—is important for policymakers and investigators (Hausberger et al., 2023).

In 2019, the CO2 emissions of the Brazilian transport sector totaled 201 Mt CO2e; over 2005–2019, its emissions increased by 42%, the second-highest increase after electricity and heat with a 58% increase (Montoya-Torres et al., 2023, Gebler et al., 2020). Only the transport sector is responsible for about 35% of the consumption of fossil fuels and for over 48% of GHG emissions in the country (Holler Branco et al., 2022).

Transportation systems are responsible for a significant portion of CO2 emissions and greenhouse gas emissions. According to Li Ye (Li et al., 2018b), transportation emissions of air pollutants and greenhouse gases are continuously increasing. Ingrao (Ingrao et al., 2021) argues that transportation should never be overlooked, as it would mean neglecting significant environmental impacts. One of these means of transportation is railway systems, widely used worldwide but also with their environmental impacts.

It is a fact that humans are fully aware that they need to take action to reduce the effects of their consumption, and a change in consumption patterns is urgent. Efforts are needed to improve the environment and address mental issues associated with the movement of goods from one place to another, especially over long distances.

Many countries are setting reduction targets, and one of the key sectors is transportation, which needs to become more sustainable. The European Union aims to reduce greenhouse gas emissions by at least 60% by 2050 (Hegedic et al., 2018). Sweden aims to achieve net-zero greenhouse gas emissions in the country by 2045, and for this, stakeholders in transportation planning, construction, and infrastructure need to reduce their impacts by half by 2030 (Hegedic et al., 2018). Life cycle assessment (LCA) in the transportation sector is becoming more widespread, and the studies conducted so far have often referred to the results obtained as a measure of the transportation flow, usually expressed as a specific weight moved over a particular distance, i.e., t-km (Ingrao et al., 2021).

To understand the true impacts of emissions, it is crucial to comprehend how goods and services are consumed by society and measure the resulting effects. Inventories are conducted to assess the environmental impact of activities known to be polluting and environmentally harmful, emitting high levels of CO_2 and greenhouse gases (GHGs), and generating solid waste. These inventories employ tools such as life cycle assessment to provide a more precise understanding.

Li Ye (Li et al., 2018b) suggests that one of the primary methods for evaluating the environmental impacts of railway transportation is studying its life cycle, which consists of four distinct phases: material extraction and processing, infrastructure construction, vehicle manufacturing, and system operation and maintenance, including end-of-life. Through quantifying these impacts throughout the railway life cycle using data from each stage, strategies can be developed to reduce costs and emissions (Rempelos et al., 2020, Shao et al., 2005, Wu and Liu, 2012, Steffen et al., 2015).

Recent studies, including the one conducted by Rempelos, Preston, and Blainey (Rempelos et al., 2020, Ma et al., 2017), have evaluated and compared the life cycle GHG emissions associated with the four most common types of sleepers in the UK railway network. Additionally, Chipindula (Chipindula et al.) conducted a study on the Dallas to Houston route, which is the busiest corridor among the 18 traffic corridors in Texas. The aim was to assess the environmental impact of the high-speed rail (HSR) system along this corridor throughout its life cycle through estimating CO_2 and GHG emissions per vehicle and dividing them by the number of passengers and kilometers traveled. A thorough analysis of emissions composition and sources was conducted for each life cycle phase to compare the current railway system with the potential HSR system. Results showed that HSR has 27% lower energy use compared to passenger cars (Zhang et al., 2021).

To identify the most resource-intensive and waste-generating phase of the railway system, it is essential to have a comprehensive understanding of resource consumption throughout the entire life cycle. Through quantifying the CO_2 and GHG emissions during the operation phase, significant efforts can be directed towards reducing emissions from rail transport. It is crucial for the pace of technological advancements in transportation infrastructure construction to surpass that of the average urban economy, ensuring the consistent reduction of energy and carbon footprints in new projects (Wei and Chen, 2020).

The effects associated with transport emissions differ across regions, technologies, fuel, and modes, but there are three overarching goals: electrification via hybridization, batteries, and fuel-cell technologies; increasing the number of public transport services; or replacing fossil fuels with their green counterparts (biofuels or synthetics). To understand the true impacts of emissions, it is crucial to comprehend how goods and services are consumed by society and measure the resulting effects. Inventories are conducted to assess the environmental impact of activities known to be polluting and environmentally harmful, emitting high levels of CO2 and greenhouse gases (GHGs), and generating solid waste. These inventories employ tools such as life cycle assessment to provide a more precise understanding (Holler Branco et al., 2022, Ramos da Silva et al., 2023, Puig-Samper Naranjo et al., 2021).

The methodology of life cycle assessment (LCA) has been employed in several transport studies, applied to different transport modes such as road (Leichter et al., 2021), rail (Ramos da Silva et al., 2023, Da Fonseca-Soares et al., 2022b), maritime (Fernández-Ríos et al., 2022), inland waterways (Plotnikova et al., 2022), and air transport (Keiser et al., 2023). Globally, researchers have conducted varied studies from a life cycle perspective in the field of rail transport, with the aim of measuring the main sources of environmental impacts, emissions, and costs. One study developed a comprehensive component-based life cycle assessment model in France (de Bortoli et al., 2020), with clear and reusable life cycle inventories (LCIs) for high-speed rail (HSR) infrastructure components.

Life cycle analysis (LCA) is used for the identification and quantification of material, energy, and emissions across all stages of the system and enables the identification of appropriate mitigation measures (Gebler et al., 2020). An LCA of a light rail trip would include the direct effects (moving the train), ancillary effects (e.g., evaluating the total greenhouse gas emissions from constructing the infrastructure and dividing it by the total number of trips), and supply chain effects (e.g., evaluating the greenhouse gas emissions from mining materials for train manufacturing and dividing it by the total number of trips served in the train’s lifetime) (Trevisan and Bordignon, 2020). Policymakers should take into consideration how policies might affect overall vehicle miles traveled, the number of vehicles on the road (i.e., traffic congestion), the availability and utilization of alternative modes of transport, and possible solutions to enhance the environmental benefits and mitigate the potential economic implications of a policy.

In light of all the facts mentioned, mapping the GHG emissions of the railway system in Pernambuco, Brazil, will aid the region in managing the environmental impacts of public transportation while improving environmental sustainability and aligning with state development goals. Through economically characterizing activities associated with increased mobility and reduced environmental impact, it becomes possible to understand the process of sustainable development within the public transport system, considering local peculiarities and potentialities. This understanding will guide the design of measures and public policies to address national environmental concerns (Wei et al., 2019b, Zhang et al., 2017a, Jasti and Vinayaka Ram, 2021).

Furthermore, this study will contribute to the theoretical and methodological framework concerning the environmental impacts of public transport activities and the development of public policies for railway infrastructure. The field of environmental impact and sustainability in the railway system remains largely unexplored, despite mechanical engineering, engines, fuels, maintenance, and urban train transportation planning being the main research areas within global railway research (Da Fonseca-Soares et al., 2022b). It highlights the need for further research in this area.

Considering interdisciplinarity as a guiding principle, this research project aims to explore the atmospheric impacts of the railway system. Its ultimate purpose is to conduct a greenhouse gas emissions inventory of the railway system in Pernambuco, Brazil, comparing it with other national railway systems, and proposing mitigation models to reduce this environmental impact. In this way, the study aims to provide strategic data for policymakers, urban planners, and other stakeholders, with the goal of promoting improvements in the railway system, mitigating air pollution, and enhancing the quality of life for future generations.

2. Materials and Methods

2.1. Study Area

The rail passenger transport system in the Metropolitan Region of Recife (RMR) directly serves the municipalities of Recife, Cabo, Jaboatão dos Guararapes, and Camaragibe, as shown in Figure 1. The rail system consists of three lines implemented in the central and southern corridors of the RMR: the electrified Central and South lines, which operate as metropolitan trains, and the Diesel line, powered by diesel traction and with the characteristics of a suburban train.

Currently, with 28 stations and a length of 39.5 km, the electric metro system in Recife transports approximately 94,000 passengers per day. The Recife metro operates on a double-track, exclusive line, electrified at 3000 Volts, with overhead wire power supply through a pantograph. It utilizes an ATC (Automatic Train Control) system with remote control for traffic and power management. The rolling stock consists of 25 electric trains, each comprising 4 cars.

The Diesel line, with 8 stations, operates between the city of Cabo, in the municipality of the same name, and the Curado neighborhood, in the city of Recife. With a length of 31.5 km, including 7 km on a double track and 24 km on a single track, the diesel train runs on a shared track with freight transportation and integrates with the electric system (metro) at Curado Station. It has 6 level crossings, and the signaling system is manual (using tokens). The rolling stock consists of 7 light rail vehicles (LRVs) (CBTU, 2021).

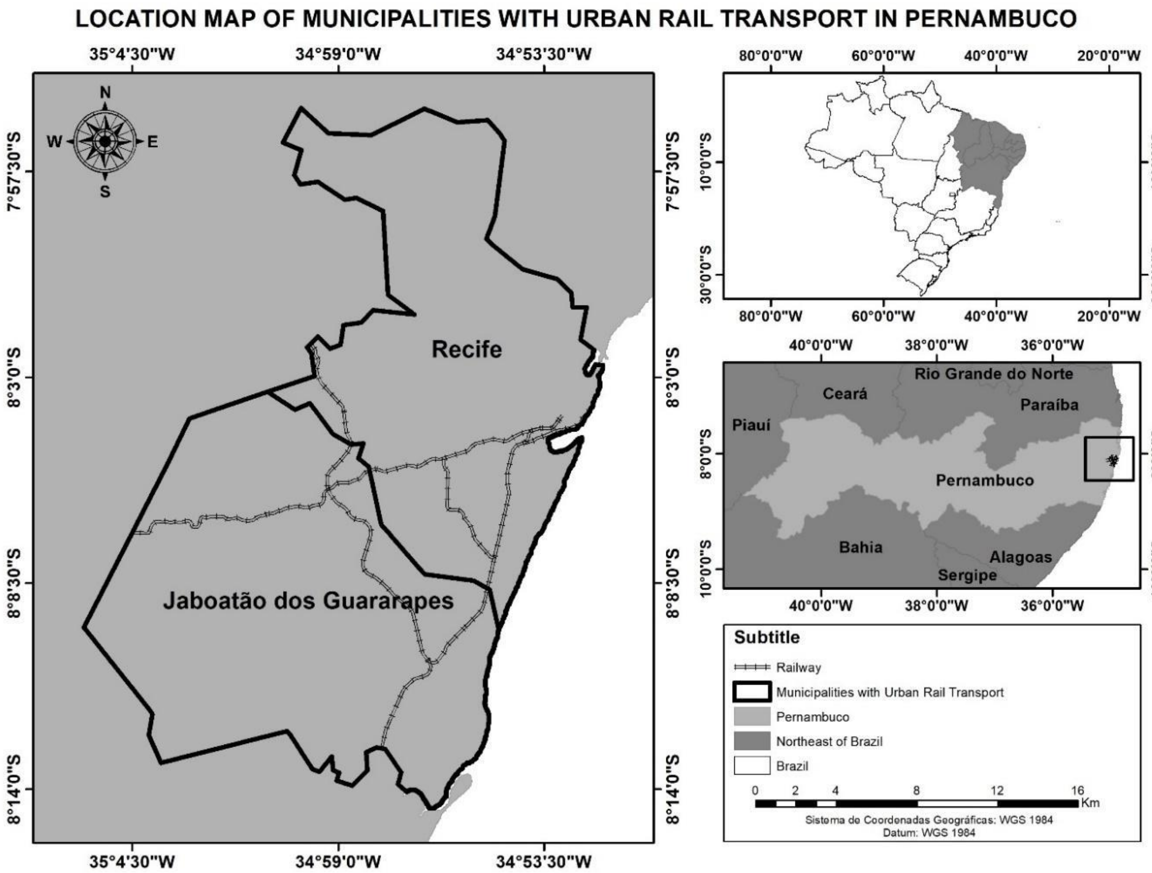

Figure 1. Geographic location of the Pernambuco urban railway.

2.2. Method

The chosen approach for investigating greenhouse gas emissions throughout the life cycle is the quantitative method, which enables a comprehensive inventory. This calculation will consider associated resource inputs such as materials, fuels, and equipment (Xu et al., 2013, Liu and Ren, 2020).

The methodology employed, known as life cycle assessment (LCA), is globally recognized for quantifying emissions across the entire life cycle of specific products or systems (Lazzerini et al., 2016, Makarchuk and Saxe, 2019, Lee et al., 2020). However, the initial definition of this methodology was intended for general application across various product types.

LCA is based on international standards like the ISO 14040 series, which establish principles and requirements for conducting life cycle studies. These standards outline the stages of LCA, including defining the study's objective and scope, data collection, the assessment of environmental impacts, and the interpretation of results (Li et al., 2018b, Rempelos et al., 2020, Chipindula et al.)

In this specific life cycle study, we have followed the framework developed based on ISO 14040-14043, which provides principles, requirements, and guidelines for conducting a reliable life cycle analysis (Chang et al., 2019, Lin et al., 2019). This framework is widely accepted and ensures consistency and quality in the obtained results.

It is important to note that the urban rail transit system does not fit solely into the category of a product, cooperation, or isolated project. Conducting an LCA in this context presents unique challenges and complexities compared to typical consumer products, requiring specific modeling adaptations (Cornet et al., 2018, Perez-Martinez et al., 2020, Costa et al., 2021)

The urban railway transport system comprises tracks, tunnels, viaducts, power facilities, depots, stations, vehicles, control centers, and more. The calculation will encompass associated resource inputs (materials, fuels, and equipment) and greenhouse gas emissions at each phase, as illustrated in Figure 2.

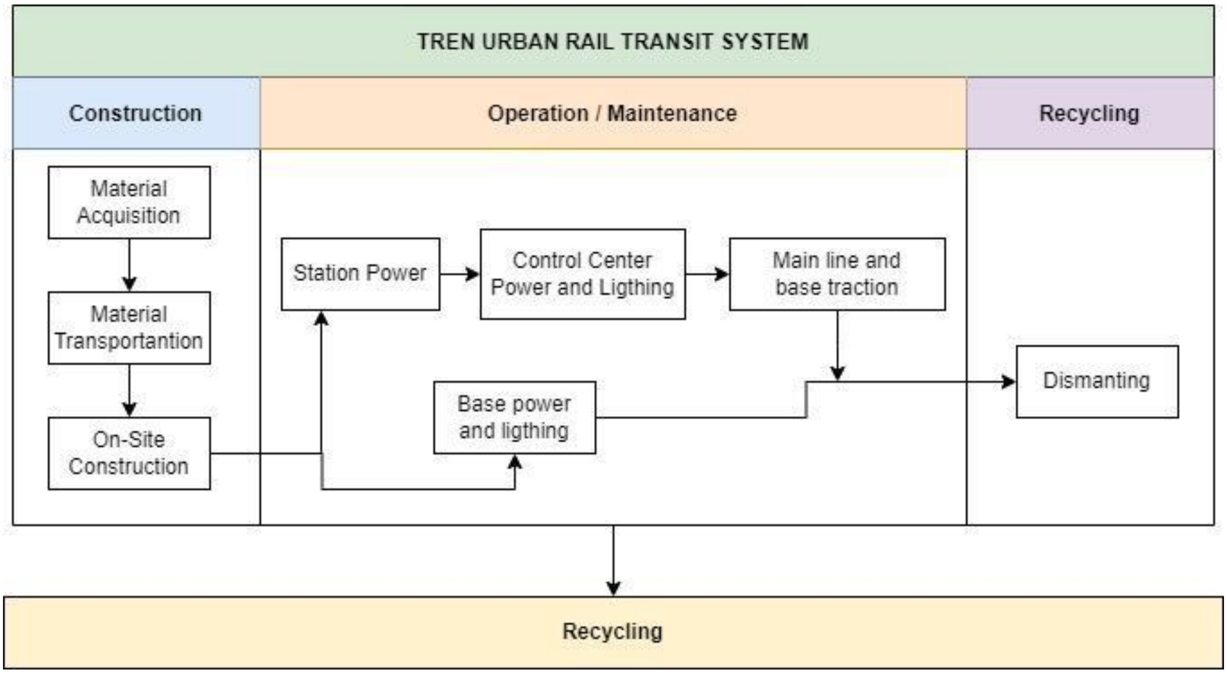

Figure 2. System boundary of GHG emission calculation of the urban rail transit system.

This study provides the total amount of gas emissions for the year 2021. However, to facilitate comparison with other international case studies, the results have been standardized based on passenger-kilometers traveled (PKT) (Yang and Zhai, 2011).

2.3. Goal and Scope Definition

This study aims to utilize a life cycle assessment methodology to establish the system boundaries of an urban rail transit system. It involves conducting an inventory of resource inputs (such as materials, fuels, and equipment) and emission outputs based on real observed data from the Pernambuco Metro. The obtained results will then be compared with findings from other similar case studies inside Brazil. The urban rail transit system comprises various components, including tracks, tunnels, viaducts, power facilities, vehicle depots, stations, vehicles, and control centers. The calculation process will encompass determining the resource inputs and greenhouse gas (GHG) emission outputs for each phase, as illustrated in Figure 2.

In the case study of the Pernambuco Metro, the functional unit considered is 1 km of construction length with a service life of 50 years. To enable meaningful comparisons with other case studies, the results are standardized per passenger-kilometer traveled (PKT).

2.4. Life-Cycle Inventory Modeling

The methodology used in this study was quantitative and based on the specifications of the Brazilian GHG Protocol Program published by the World Resources Institute (WRI, 2010). The inventory process forms the foundation of the Brazilian GHG Protocol program for accounting, quantifying, and reporting corporate greenhouse gas emissions inventories, following the parameters of ISO 14040-14043, which determine the framework, principles, requirements, and guidelines that should be included in a life cycle study (Yang and Zhai, 2011).

A study was conducted to identify the sources of greenhouse gas (GHG) emissions within the railway system of Pernambuco, based on the year 2021. The GHG Protocol tool was used for this purpose, following the activity categories and emission factors associated with gases.

The modeling process will focus on calculating the inputs of associated resources (materials, fuels, and equipment) and the outputs of greenhouse gas emissions in each relevant phase. These phases will be categorized into sectors such as maintenance, operation, transport, and material acquisition, allowing for a comprehensive analysis of the emissions throughout the railway system's life cycle.

Life-cycle GHG emissions were estimated using Equation (1), as follows:

$$1.\quad E = (Q1 + Q2 + Q3 + Q4)/L$$

where

E = GHG emissions by extension of the urban rail transport system (t CO_2e/km);

Q1 = Maintenance Emission Factor;

Q2 = Operation Emission Factor;

Q3 = Transport Emission Factor;

Q4 = Material Acquisition Emission Factor;

L = the length of the rail line (km).

Under the relevant category, information on GHG emissions was inputted based on railway data, such as electricity consumption, fuel consumption, releases from air conditioning and fire extinguishers, fossil fuel combustion, material and personnel logistics, and other activities that may emit GHGs.

2.5. Data Collection

This research was conducted as a life cycle study following the structure developed based on ISO 14040-14043, which establishes the principles, requirements, and guidelines for conducting life cycle assessments. To perform the greenhouse gas (GHG) inventory of the railway system in the state of Pernambuco, Brazil, data were collected from various sources:

Fuel and traction energy consumption: The Pernambuco railway operates on both diesel and electric energy, depending on the section of the rail network. Therefore, data on traction electricity consumption by trains and the diesel fuel used by light rail vehicles were collected over the course of one year.

Maintenance and auxiliary activities: Auxiliary activities related to the railway, such as infrastructure maintenance, station operations, lighting, the refrigeration of facilities, and carbon dioxide fire extinguishers, were considered. Data related to the fuel consumption of auxiliary vehicles, electric energy used in stations and administrative buildings, fugitive emissions from train and facility refrigeration systems, and fugitive emissions from carbon dioxide fire extinguishers, as well as the electric energy used in train maintenance, were collected.

Data accuracy: To obtain accurate GHG emission calculations, specific emission factors for each source were considered. For instance, in the case of gasoline, it was taken into account that approximately 27% of this fuel in Brazil is composed of ethanol, while for diesel, the ethanol percentage is around 7%. Therefore, the amounts of ethanol, pure gasoline, and pure diesel were separated to calculate the GHG emissions using specific emission factors for each type of fuel.

Distance traveled: The total distance covered by trains was recorded to calculate emissions per unit of distance and enable comparisons with other railway systems.

Demographic and demand data: Data regarding the number of passengers were fundamental to estimate total emissions and calculate emissions per passenger unit.

The data are reliable, up to date, and the calculations adhere to the standards of the Greenhouse Gas Protocol (GHG Protocol), recognized internationally for conducting GHG inventories.

However, there was a limitation in data collection regarding construction materials and building maintenance, which hindered the calculation of GHG emissions associated with the construction and maintenance of the railway infrastructure in Pernambuco. Due to the railway's long history, relevant information on construction materials over the years was lost over time.

In this article there is a summary of all the data collected on traction and building electrical energy consumption, diesel consumption by locomotives and light rail vehicles, fuel consumption of auxiliary vehicles and maintenance logistics, fugitive emissions from refrigeration systems and extinguishers, among other factors already highlighted.

2.6. Calculation Tool

The GHG Protocol tool was created to calculate greenhouse gas (GHG) emissions from all sources within the company and assist in the inventory development process. It was developed using an electronic spreadsheet along with the Visual Basic tool, based on the GHG Protocol methodology. Each spreadsheet was programmed with formulas and emission factors to quantify the emissions, providing information about emissions by scope and summaries (Costa et al., 2021).

Each greenhouse gas has the capacity to retain heat at a specific intensity, which can be compared to the capacity of carbon dioxide to perform the same function. Therefore, the tool works with a transformation model that converts emissions from different sources into carbon dioxide equivalents (CO2e) conform table 1. CO2e is a metric used to equalize emissions of various GHGs based on their relative importance compared to CO2 in producing a given amount of energy (per unit area) several years after the emission impulse. The calculation of CO2e involves conversions, with the global warming potential (GWP) table proposed by the IPCC being the most commonly used (Perez-Martinez et al., 2020).

Table 1. Building energy consumption data.

GAS	GWP-100
CO_2	1
CH_4	25
N_2H	298
HFC-125	3500
HFC-134a	1300
HFC-143a	1430
HFC-152a	124
CF_4	7390
C_2F_6	12,200
SF_6	22,880

With the data collected, the spreadsheet was filled, and the calculation tool performed the necessary calculations for equivalent emissions. All data were input into the spreadsheet, which uses the conversion model for each greenhouse gas that is capable of retaining heat at a specific intensity, comparable to the capacity of carbon dioxide (Jasti and Vinayaka Ram, 2021, Li et al., 2018b, Lee et al., 2020).

3. Results

3.1. Case Study: Pernambuco, Brazil

The urban railway transportation system in Pernambuco, Brazil has a rich history spanning over 150 years. The decision by the Brazilian government to repurpose the defunct freight railway for the construction of the urban railway was a strategic one. However, this choice has resulted in a scarcity of reliable information concerning the actual construction process of the urban railway in northeastern Brazil. Consequently, the greenhouse gas emissions inventory pertaining to the railway construction is not addressed within the scope of this particular case study.

Nevertheless, various studies, including the research conducted by Ye Li (Li et al., 2018b), have consistently indicated that the emissions attributed to railway construction constitute a minor proportion, accounting for less than 5% of the overall life cycle emissions of a railway system. Hence, the absence of construction data does not exert a significant impact on the greenhouse gas emissions inventory analyzed in this study.

3.2. Operation and Maintenance

The energy consumption during the operation and maintenance phases can be categorized into eight sources: fugitive emissions, station energy and lighting, electric traction, diesel traction, base energy and lighting (workshop and administration), control center energy and lighting, transportation, and materials. Tables 2–6 provide a detailed description of the scope of each source, serving as a reference for future life cycle assessment (LCA) studies on urban railway transportation systems.

To ensure data availability and accessibility, we have selected 2021 as the base year for estimating the overall emission level during the operation and maintenance phases. Data from the Brazilian urban train company reveals the total energy usage in station facilities and building energy, along with their associated emissions, as presented in Table 3. Additionally, Table 3 also includes information on the total energy and resources consumed in logistic transportation, considering vehicle arrivals and departures, and their corresponding emissions.

Table 2. Data on building energy consumption.

	Energy Consumption	**Emissions (t CO2e)**	**CO2-Biomass**
Electric (building)	8431.12	624.24	-

Table 3. Data on energy consumption per logistics transport.

	Energy Consumption	**Emissions (t CO2e)**	**CO2-Biomass**
Diesel	8764	20.87	2.04
Gasoline	29,083	45.97	11.26

Table 4. Gases released by the air conditioning and fire extinguisher.

	Energy Consumption	**Emissions (t CO2e)**	**CO2-Biomass**
gas garbonic	434	319.42	-

Table 5. Tractive energy data of the electric train.

	Energy Consumption	**Emissions (t CO2e)**	**CO2 -Biomass**
Electric (traction)	51,663,668	3774.70	-

Table 6. Tractive energy data of the diesel train.

	Energy Consumption	**Emissions (t CO2e)**	**CO2-Biomass**
Locomotive	27,480	1319.61	129.79
Light Rail Vehicles	551,491	65.73	6.49

Table 4 offers a comprehensive summary of greenhouse gases emitted from air conditioning systems and fire extinguishers employed in the railway system throughout 2021, including the emissions associated with them. Tables 5 and 6 outline the energy consumption for electric and diesel train traction, respectively, with traction energy accounting for approximately 84% of the total greenhouse gas emissions.

The railway system in Pernambuco, Brazil, has a portion of trains powered by diesel traction and another portion powered by electricity. As a result, the emissions from electricity account for 61% of the total emissions, while emissions from diesel traction are around 23%. This differs from most railway systems around the world, which are predominantly powered by electricity (Figure 3).

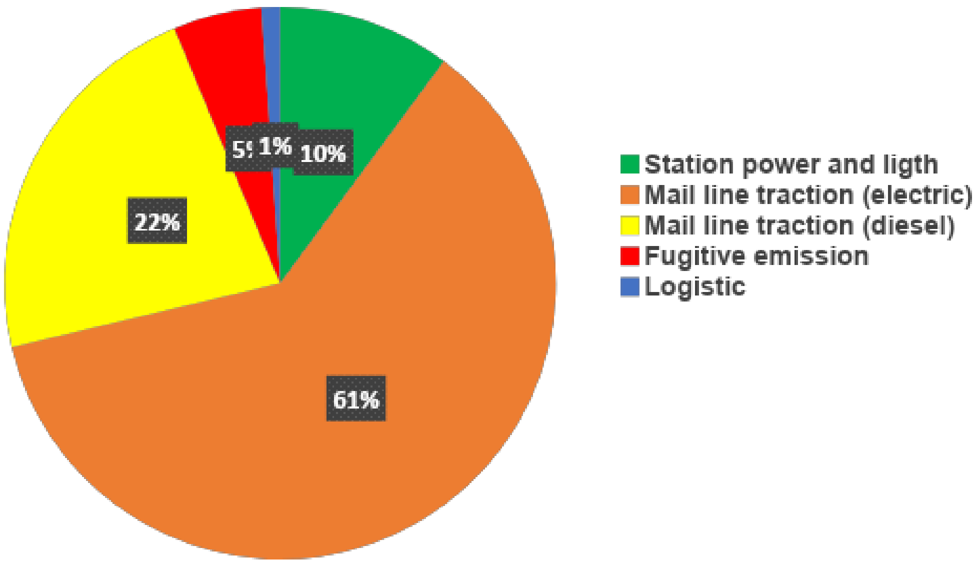

Figure 3. Composition of consumption and emissions.

Although the emissions are not directly generated by the electricity consumed during operation, the LCA calculations encompass greenhouse gas emissions arising from energy generation and transmission processes. In 2021, the average annual electricity consumption for train traction in Pernambuco’s railway transportation during the operation phase reached 51.7 million kWh. The corresponding greenhouse gas emissions from electricity utilized for train traction amounted to 3774.70 t CO2e. For the diesel train system, which consumed 578,978 L of diesel fuel in 2021, the calculated greenhouse gas emissions were 1385.34 t CO2e.

Through aggregating emissions from other energy sources, the total annual greenhouse gas emissions from operation and maintenance summed up to 6170.54 t CO2e. Assuming a total service life of 50 years, the estimated total greenhouse gas emissions from the life cycle of operation and maintenance in Pernambuco’s railway system amounted to 308,550 t CO2e.

3.3. Disassembly and Recycling

The development of urban railway transportation in northeastern Brazil occurred relatively late, starting with the opening of the first system in 1985. This involved repurposing some trains from the Rede Ferroviária and acquiring new ones. However, there is currently a lack of reliable data regarding the dismantling and recycling of the urban railway transportation infrastructure in this region of Brazil. As a result, the dismantling process is not addressed in this particular case study.

4. Discussion

4.1. Comparative System

This study aims to emphasize the importance of conducting a comparative analysis of traction emissions, station operation, and infrastructure in different urban railway transportation systems across Brazil. It should be noted that there is limited availability of related studies, and the comparative analysis is conducted within the same scope whenever possible, drawing on data and information from specialized literature and various case studies with diverse local parameters (Bozzo et al., 2011).

The results obtained from this comparison can provide valuable insights into the potential for reducing emissions in urban railway transportation systems and contribute to the establishment of emission reduction targets in the Brazilian context. This study compares greenhouse gas emissions (GHE) from urban railway systems, including the metro systems in Recife, São Paulo, and Rio de Janeiro, as well as the urban railway (train) in Rio de Janeiro.

Furthermore, the reasons for data discrepancies among these cities are explored. To facilitate the comparison, emission intensities for each city are standardized per passenger-kilometer traveled (PKT). Standardizing emission intensities per PKT enables fairer comparisons and allows for the identification of areas for improvement in each railway system. This approach takes into account both the number of passengers transported and the distance traveled, thus providing a more equitable evaluation of environmental performance (Boschiero et al., 2019).

Therefore, this comparison of emissions standardized per PKT in different urban railway systems offers valuable insights into disparities and provides important information for the development of more sustainable and emission-efficient transportation strategies. In 2021, the total GHE from electricity and diesel consumption for traction in the metro system of Pernambuco amounted to 5160.04 tCO2e, based on a total of approximately 32 million passengers, resulting in traction emissions of 4 g CO2e/PKT.

In 2016, the total GHE from electricity consumption for traction in the metro system of Rio de Janeiro reached 14,963 tCO2e. With a total passenger volume of approximately 245 million, traction emissions were measured at 5.5 g CO2e/PKT. The total traction emissions in 2016 for the railway system in Rio de Janeiro were 22,273 tCO2e, with a total passenger volume of 182 million (Andrade and D'Agosto, 2016, Rio, 2016). Hence, traction emissions on the Rio de Janeiro railway amounted to 5.6 g CO2e/PKT (SuperVia, 2016). According to the governance report of the metro system of São Paulo in 2022, traction emissions for the São Paulo metro were 6 g CO2e/PKT (Perez-Martinez et al., 2020, Paulo, 2022). In Figure 4 presents the comparison of traction emissions per PKT in these three locations.

Based on these results, Pernambuco exhibited the lowest traction emissions per PKT, while the São Paulo metro had the highest emissions per PKT. Traction emissions are influenced by factors such as train characteristics, track conditions, and operational modes, among others. However, since these contributing factors are not the main focus of this study, they were not detailed within this research.

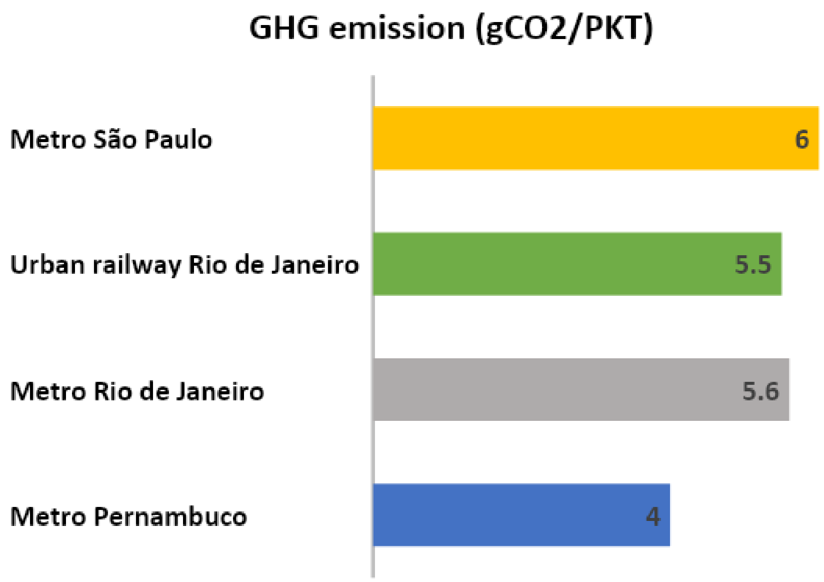

Figure 4. Traction emission per PKT.

These results can be attributed to three factors: the carbon intensity of electricity supply, passenger volume, and the efficiency of electricity use in urban railway transportation. The adopted greenhouse gas emission factors for electricity were similar across the case studies. However, there are notable differences in train flow between the Pernambuco metro and the metros in Rio de Janeiro and São Paulo, with much longer intervals between trains in Pernambuco. Additionally, the Pernambuco metro has a smaller network extension compared to Rio de Janeiro and São Paulo.

Typically, higher passenger occupancy rates result in lower emissions per PKT. However, this pattern does not hold true for the São Paulo metro due to its extensive railway network, which serves a larger population than the other three systems being compared.

It's important to note that the data for Rio de Janeiro is from 2016, predating the data from the other systems. The relatively high emissions in Rio de Janeiro may be partially explained by the lack of available energy-saving technologies at that time.

Greenhouse gas (GHG) emissions in railway systems can vary considerably due to various factors that affect the operation and infrastructure of these systems. One of the main influences is the type of energy used to power the trains, which has a significant impact on the total emissions of the railway system (Jasti and Vinayaka Ram, 2021, Kurczyński, 2021). In the case of the Pernambuco subway, it stands out from other systems compared in this article because it uses a combination of electric and diesel energy, with the latter being a fossil fuel with high GHG emissions.

Furthermore, the number of passengers and freight transported via railway systems has a direct impact on GHG emissions (Lee et al., 2020). Highly busy systems with high demand, such as São Paulo's, may show greater efficiency in terms of emissions per passenger-kilometer. However, this efficiency is not reflected when comparing São Paulo's system with other railway systems with lower passenger flow, such as Rio de Janeiro's, for example. This discrepancy can be partly explained by the energy efficiency of train engines, which directly influences GHG emissions. More modern and energy-efficient trains tend to emit fewer GHGs per kilometer traveled compared to older and less efficient trains. Additionally, operational factors such as the use of traffic control technologies, efficient operating practices, and proper maintenance also play a significant role in reducing GHG emissions in railway systems.

However, to fully understand the specific differences between São Paulo's system and others, it is essential to conduct a detailed scientific investigation within that particular system. This would allow for the identification of factors that may be related to the high GHG emission rate in this specific system.

It is crucial to emphasize that GHG emissions are influenced by a combination of several factors. Therefore, for a comprehensive assessment of GHG emissions in compared railway systems, it is necessary to consider all relevant variables and conduct a thorough investigation to analyze and compare each of them. The existence of this gap in the current article highlights the importance of future research that can fill this knowledge gap and enhance our understanding of the environmental impact of railway systems.

4.2. Mitigation of GHG Emissions

Mitigating greenhouse gas (GHG) emissions in railways is essential to reduce the environmental impact of this transportation sector.

In the railway system of Pernambuco, electric energy is the main source of GHG emissions, as demonstrated in graph 01. Adopting electrified railway systems, using renewable sources such as solar energy, can significantly decrease GHG emissions. Installing solar panels on station rooftops can significantly reduce electricity consumption, taking advantage of the abundant sunlight in the northeast region of Brazil, where Pernambuco is located.

Currently, Pernambuco's light rail operates on diesel energy, a fossil fuel with high GHG emission potential. Replacing this fuel with renewable energy can substantially cut down on GHG emissions. A study by Mariko, which analyzed the feasibility of photovoltaic energy for Brazilian light rail, revealed that installing photovoltaic systems on the rooftops of the fleet operated in Brasilia's railway could save around BRL 800,000 and reduce CO2 emissions by 540 tons over 10 years (Carneiro and Soares, 2020).

Efficient electricity use plays a crucial role in reducing energy consumption and emissions in urban railway transportation. Recycling is an effective method to save energy, as demonstrated by Delhi's metro. Electricity generated during train braking is repurposed for other operational modes, resulting in nearly 35% of Delhi Metro's electricity consumption being regenerated by the system (Doll and Balaban, 2013).

Additionally, managing energy consumption in stations and administrative buildings can further decrease GHG emissions. Mariko's research, which implemented a conscious and sustainable energy consumption program in a Brazilian Northeast railway system, achieved a 56% reduction in monthly electricity consumption and over 50% in GHG emissions (Carneiro et al., 2022). Applying energy-saving techniques like this can be beneficial in reducing traction emissions in Brazilian railway systems.

Improving the energy efficiency of Pernambuco's light rail is an important form of mitigation. This can be achieved through engine modernization, traction system enhancement, route and speed optimization, and the use of more efficient technologies. As demonstrated by Dariusz Kurczyński (Kurczyński, 2021), a modern engine with a common rail system, powered by biodiesel RME (rapeseed methyl ester) and its blends with diesel, can reduce average concentrations of carbon monoxide, hydrocarbons, and particulate matter.

5. Conclusions

The objective of this research was to calculate greenhouse gas (GHG) emissions throughout the entire life cycle of the railway system in Pernambuco, Brazil, using real observed data. Additionally, a comparative analysis was conducted to understand the level of emissions in the national context and provide guidance for future emission reduction efforts. This analysis also aimed to provide concrete data on environmental impact to policymakers, urban planners, and other stakeholders who seek to promote improvements in the railway system towards a sustainable railway system for future generations.

The results showed that the total GHG emissions for the entire life cycle of the Pernambuco railway system, considering its construction length, amounted to 6170.54 metric tons of CO2 equivalent (tCO2e). With a lifespan of 50 years, the projected emissions are estimated to reach 308,550 tCO2e.

These findings offer valuable insights into the environmental impact of the railway system in Northeast Brazil, serving as a basis for identifying areas that need improvement and guiding future actions to reduce GHG emissions. However, due to the railway system's construction over 150 years ago, using the cargo transportation system of the federal railway network, there is a lack of concrete data on the quantity of construction materials used, making it impossible to calculate GHG emissions during the construction phase.

The urban railway system in Pernambuco differs from the rest of the country as it combines trains powered by electricity and diesel. When compared to other national systems in the operation and maintenance phase, the traction emissions of the Pernambuco railway system were 4 g CO2e per passenger-kilometer traveled (PKT), which is competitive with the emissions of the São Paulo and Rio de Janeiro metros and the Rio de Janeiro railway. This is noteworthy considering the higher passenger volume in the latter systems. However, there is still significant potential for energy savings in the operation phase, particularly in stations and central buildings that could utilize solar energy. The northeastern region of Pernambuco, located close to the equator, receives abundant sunlight throughout the year, making solar energy a viable renewable option (Carneiro et al., 2022). Implementing more efficient ventilation structures in metro stations and using energy-saving lighting solutions like LED lights can effectively reduce emissions from these stations (Carneiro and Soares, 2020).

For future research, it is recommended to conduct a more detailed comparative analysis that takes into account system boundaries, GHG accounting methods, and datasets from different case studies. This approach will provide a comprehensive and accurate understanding of emissions in diverse contexts.

Furthermore, the development of a comprehensive estimation tool and a standardized benchmark applicable to various areas, equipment types, structures, and techniques would be highly beneficial. This would facilitate the collection and analysis of consistent and comparable data, enabling a more precise assessment of GHG emissions in different railway systems.

This report provides, in addition, real-world experience and guidance from government and industry with years of experience in inventory. A comprehensive life cycle model of the entire railway system was developed. This report is meant as a complement to policymakers' efforts and provides, in addition, real-world experience and guidance from government and industry with years of experience in the charging space. Given the role of the railway system in Pernambuco's economy, especially as it relates to the distribution of goods and the provision of services, the Fuels Institute is dedicated to informing comprehensive discussions about the various policy options available to balance the various needs of the market while achieving significant reductions in transportation emissions.

In conclusion, conducting more in-depth analyses, improving tools, and establishing enhanced benchmark standards will contribute to the assessment and management of GHG emissions in the railway sector. This will allow for the identification of areas for improvement and the development of effective strategies to reduce emissions.


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CHAPTER 04

A TOOL OF LIFE-CYCLE ASSESSMENT TO DETERMINE GREENHOUSE GAS EMISSIONS OF THE URBAN RAILWAY SYSTEM IN THE NORTHEAST OF BRAZIL

The results presented in this chapter were submited in the journal Transportation Research Part D: Transport and Environment
Journal Rank Europe: JCR 7.6; CiteScore 12,3 – Q1 (*Engineering, Multidisciplinary*)
Journal Rank Brazil: A1 (Environmental Studies) / A1 (Engineering I)

1. Introduction

In recent decades, the rapid growth of population and urbanization has led to an increasing demand for alternative transportation services in societies. This emerging trend in mobility requires swift responses from public transportation systems, which must offer reliable, comfortable, and economically and environmentally sustainable services. As economies thrive and cities expand, an efficient transportation infrastructure can play a vital role in mitigating environmental issues, diseases, and fatalities in urban areas (Kaewunruen et al., 2020, Lin et al., 2019).

The issue of greenhouse gas emissions (GHG) has become one of the most pressing and crucial concerns on a global scale, driven by the growing understanding of its implications for climate change. As an essential element of worldwide initiatives aimed at addressing climate transformations, multiple sectors have been examined regarding their contribution to GHG emissions. In this context, the railway transportation system has emerged as a fundamental area of investigation, given its significance in urban mobility and freight transport (Kaewunruen et al., 2020, Shi et al., 2010).

The railway system, although often seen as a more sustainable transportation option compared to road and air modes, is not exempt from significant environmental impacts. The combustion of fossil fuels, such as diesel, to power trains is one of the primary sources of GHG emissions in the railway sector. This generates carbon dioxide (CO2) and other gases that contribute to global warming (Trevisan and Bordignon, 2020).

A comprehensive literature review on greenhouse gas emissions in the railway system unveils a complex interplay of factors contributing to the generation of these gases. Studies have indicated that electrification of the railway system, replacing diesel traction with electricity, can substantially decrease GHG emissions. The adoption of cleaner and renewable energy sources for the electricity used in trains can be a crucial step in mitigating emissions (Gee and Dunn, 2015, Zhu et al., 2020, Khodaparastan et al., 2019, Zhu et al., 2021a, Krueger et al., 2021, Carneiro and Soares, 2020, Zare et al., 2021, Kurczyński, 2021, Thongchai and Lim, 2020, Li and Lin, 2021, Zhu et al., 2011).

Additionally, the GHG of operations and the adoption of traffic management technologies can influence GEE emissions. More modern and energy-efficient train models tend to release lower amounts of GHG per kilometer traveled, in contrast to older and less efficient models. Appropriate maintenance measures and route optimization also prove to be contributing factors in reducing emissions (Aminzadegan et al., 2022, Chen, 2022, Da Fonseca-Soares et al., 2023, Gulcimen et al., 2021).

Another relevant aspect is waste management and fugitive emissions, which can occur during the transportation and maintenance processes of railway systems. Proper maintenance of railway tracks and appropriate management of train components can minimize these emissions (Aminzadegan et al., 2022, Chen, 2022).

The utilization of Life Cycle Assessment (LCA) methods has proven to be a highly useful tool for examining the effect of GEE emissions throughout the entire lifecycle of the railway system. These methods enable the analysis of emissions from material production to train operation and maintenance, providing a comprehensive understanding of the emissions involved (Ramos da Silva et al., 2023, Hausberger et al., 2023, Keiser et al., 2023, Da Fonseca-Soares et al., 2023, Merchan et al., 2020, Gebler et al., 2020).

The environmental impact of greenhouse gases in the railway context highlights the intricate interplay of factors influencing emissions, underscoring the significance of comprehensive approaches to mitigation. Electrification, enhanced operational efficiency, the adoption of clean energy sources, and the use of life cycle analysis models emerge as fundamental elements to attenuate the environmental impact of GHG emissions in the railway system, thereby contributing to the promotion of sustainability and the fight against climate change (Hausberger et al., 2023, Lee et al., 2020).

While there are studies that delve into environmental performance through Life Cycle Assessment (LCA), there is a shortage of literature specifically examining life cycle assessment in railway systems, particularly concerning greenhouse gas emissions. (Da Fonseca-Soares et al., 2022b). Consequently, there is an urgent need to research optimal methodologies for greenhouse gas inventory in the railway system and identify effective mitigation strategies for these emissions.

The development of a greenhouse gas inventory in the railway system stands as an indispensable tool to underpin effective public mitigation policies. By providing meticulous and precise data on emissions, this inventory allows for a focused approach to reducing emissions throughout the entire lifecycle of the railway system. Such a focus directly contributes to the promotion of environmental sustainability, addressing climate transformations, and building a more resilient and adaptable future (Thondoo et al., 2020, Hamurcu and Eren, 2020, Li et al., 2018b, Chang et al., 2018).

Therefore, the objective of this study is to develop a methodology that allows the determination of greenhouse gases in the railway system. As a result, this work calculated, using this methodology, the greenhouse gas emissions generated by the metro system in the northeastern region of Brazil, which comprises the states of Paraíba, Pernambuco, Rio Grande do Norte, and Alagoas. This study aims to compare these emission results with studies from other states in this region and with global railway greenhouse gas emissions. Additionally, it seeks to analyze ways to mitigate these greenhouse gas emissions to formulate more effective public and environmental policies within the railway transportation system of these regions. The analysis will employ a life cycle assessment methodology to accurately map the carbon footprints associated with these emissions.

2. Materials and Methods

2.1 Study area

The research was conducted on the railway system in the northeastern region of Brazil, specifically focusing on the states of Paraiba, Pernambuco, Rio Grande do Norte, and Alagoas, which are equipped with this transportation infrastructure.

The railway was distributed in different municipalities in the states of northeastern Brazil, as shown in Figure 1: Paraiba (João Pessoa, Cabedelo, Santa Rita, Bayeux); Alagoas (Rio Largo, Setuba, Maceio); Rio Grande do Norte (Ceará-Mirim, Extremoz, Natal, Parnamirim); Pernambuco (Recife, Jaboatão dos Guararapes).

The rail system encompasses an electric metro that operates through an overhead power grid for electrification, along with a diesel train. Spanning over 200 km in length, this extensive transportation network caters to an average daily ridership of 250,000 passengers.

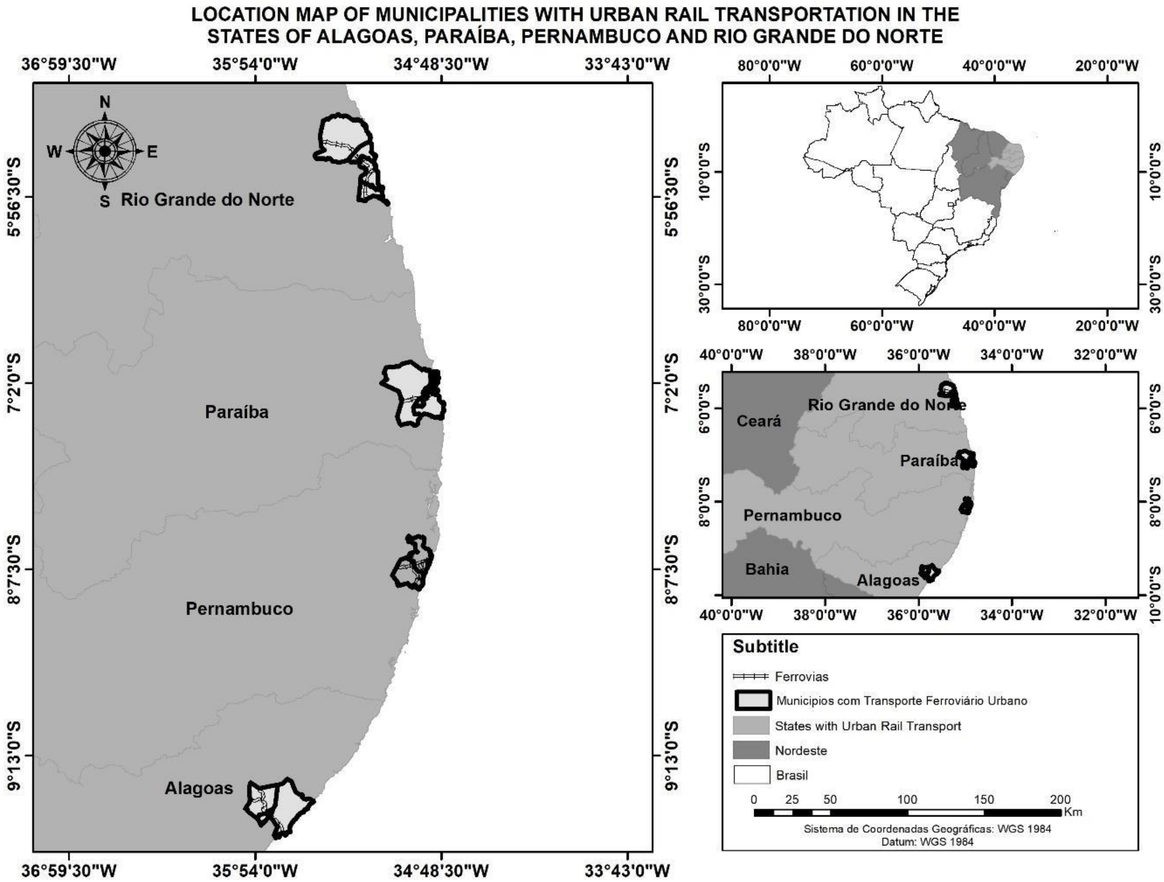

Figure 1. Location map of the Paraiba Railway System, Brazil

2.2 Methods

The method to be employed in this investigation will be quantitative to inventory emissions across the lifecycle, with calculations taking into account associated resource inputs (materials, fuels, and equipment).

Life Cycle Assessment (LCA) is an international methodology used to quantify the emissions of specified products or systems throughout their entire lifecycle (Lazzerini et al., 2016). However, this methodology was originally defined to be applied to various types of products in a generalized manner. Therefore, conducting an LCA for a railway system can be much more complex than for consumer products in general. Since the urban railway transportation system is not merely a product, commodity, or project, none of the standards can fully apply to it (Liljenstrom et al., 2019).

Choices regarding system boundary definition, model parameterization, and data selection can significantly affect the calculated results(Olugbenga et al., 2019).

This life cycle study was conducted following the framework developed based on ISO 14040-14043, which establishes the structure, principles, requirements, and guidelines that should be included in a life cycle study.

As mentioned above, conducting an LCA for an urban railway transit system can be more challenging and complex than for general consumer products. Modeling may not be sufficient and may require adaptations. Selections concerning system boundary definition, model parameterization, and data selection can significantly impact the calculated results.

In this study, the parameters of the GHG Protocol Product Standard from the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) will be used. This standard is based on a life cycle and attributional approach and relies on ISO 14040 and ISO 14044 standards for life cycle assessment studies.

There is an adapted version for the Brazilian product system, but it has not been thoughtfully tailored to the railway system, lacking in its modeling parameters the diesel railway system currently used in northeastern Brazil. This investigation will model this calculation parameter based on the existing indices from the World Resources Institute.

The urban railway transportation system comprises tracks, tunnels, viaducts, power facilities, depots, stations, vehicles, control centers (Olugbenga et al., 2019). The calculation will encompass associated resource inputs (materials, fuels, and equipment) and greenhouse gas emissions outputs at each phase, following Figure 2.

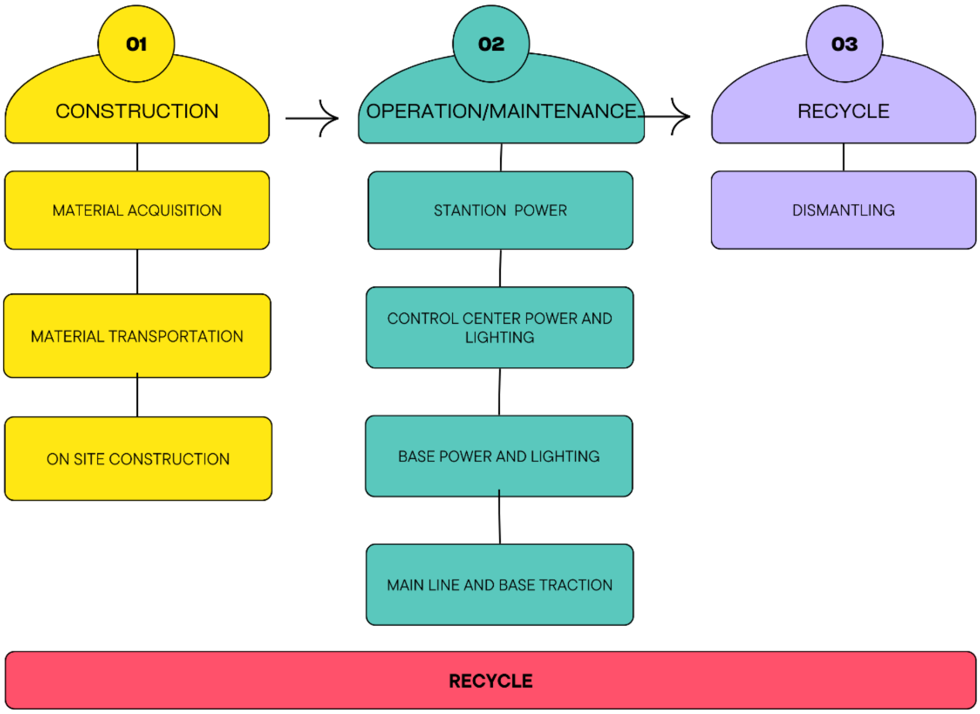

Figure 2. Flowchart of the Greenhouse Gas Emissions Inventory methodology

This work displays the total amount of gas emissions based on the year 2022; however, to compare with other international case studies, the results were standardized per passenger-kilometer traveled (PKT) (Li et al., 2018b)

2.3 Life cycle inventory modeling

The methodology used in this study was quantitative and based on the specifications of the Brazilian GHG Protocol Program published by the World Resources Institute (Li et al., 2018b). The inventory methodology is the basis of the Brazilian GHG Protocol program for corporate greenhouse gas emissions accounting, quantification, and reporting. This methodology follows the parameters of ISO 14040-14043, which establish the framework, principles, requirements, and guidelines for a life cycle assessment (Liljenstrom et al., 2019, Kimball et al., 2013, Puig-Samper Naranjo et al., 2021).

Each greenhouse gas has the ability to trap heat to a certain degree, and this capacity can be compared to the ability of carbon dioxide to perform the same function. Therefore, a model of transforming emissions into carbon dioxide equivalent (CO2-e) was implemented. CO2-e is a metric used to equate emissions of various greenhouse gases based on their relative importance to carbon dioxide in terms of energy production (per unit area) several years after an emission impulse. For calculating CO2-e, various conversions are employed, with the most common being Global Warming Potential (GWP) (Rempelos et al., 2020, Chang et al., 2019, Wang et al., 2018, Zhang et al., 2017a) as shown in Table 01.

Table 01. Category of factors with greenhouse gas emissions

GAS	GWP-100
CO_2	1
CH_4	25
N_2H	298
HFC-125	3500
HFC-134a	1300
HFC-143a	1430
HFC-152a	124
CF_4	7390
C_2F_6	12200
SF_6	22880

Source: Adapted (EPA, 2016)

Due to Brazil's northeastern railway system having existed for over 150 years, there are no data available regarding its construction, such as project budget spreadsheets with detailed and complete records of the construction process. As a result, this research will not cover the emissions from the railway's construction phase.

The modeling will involve calculating inputs of associated resources (materials, fuels, and equipment) and the outputs of greenhouse gas emissions at each phase, categorized by maintenance, operation, transportation, and material procurement sectors (Chang and Kendall, 2011b, Montoya-Torres et al., 2023).

The life cycle greenhouse gas emissions were estimated using Eq. (1), as follows:

1. $E = (Q1 + Q2 + Q3 + Q4) / L$

Where;

E = Greenhouse gas emissions per unit length of urban railway transportation system (t CO_2e/km);

Q1 = Maintenance Emission Factor

Q2 = Operation Emission Factor

Q3 = Transportation Emission Factor

Q4 = Material Procurement Emission Factor

L = represents the length of the railway track (km)

2.3.1 Calculation of operation and maintenance emission source

Fugitive Emission

The calculation of carbon dioxide equivalent (CO_2-e) emissions from refrigeration, air conditioning, and fire extinguishing equipment that use greenhouse gases (GHGs) in their operation can be performed following these general steps: Identifying all refrigeration, air conditioning, and fire extinguishing equipment present in the system; identifying the GHGs by identifying the specific greenhouse gases used in each equipment. Some examples include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6); Obtain the necessary data to perform the calculations, including information about the quantity of GHGs used, specific emission factors for each GHG, and equipment efficiency.

To calculate GHG emissions from Refrigeration and Air Conditioning Equipment and Fire Extinguishers using a life cycle stage approach, the equation is as follows:

$$2.\quad E = (EUN + EUE + EUD) * GWP$$

Where,

E = emissions in CO2-e (kg);

EUN = emissions from the installation of new units: gas used to charge the new equipment minus the equipment's capacity (the difference corresponds to losses to the atmosphere);

EUE = gas added to existing units as maintenance by the organization or supplier (does not include pre-charging done by the manufacturer);

EUD = emissions from the disposal of old units: capacity of the discarded unit minus the amount of recovered gas (the difference corresponds to losses to the atmosphere);

GWP = Global Warming Potential of greenhouse gases (Table 01):

Rail transportation

The rail fleet in northeastern Brazil is characterized by three types of trains: Locomotives, Light Rail Vehicles (VLT), and Electric Trains. The first two utilize commercial diesel oil as fuel.

In Brazil, some fossil fuels are legally required to have a percentage of biofuel incorporated before being sold to the final consumer. Due to this regulation, the formula already separates these percentages before calculating emissions. Therefore, the calculation is done separately for pure fossil diesel oil and biofuel, as shown in Table 02.

Table 02. Inventory Parameters for the year 2022

Year	Parameters	Units	Annual Average
2022	Perc. of ethanol in gasoline	%	27%
2022	Perc. of biodiesel in diesel	%	7%

Source: Adapted (BRAZIL, 2001)

Initially, the values of fossil fuel and biofuel are separated. Then, emission factors for the use of fossil fuels in mobile sources are used for greenhouse gas conversion, as shown in Table 03.

Table 03. Emission Factors for Fossil Fuel Diesel Oil

Kg CO2 / liters	Kg CH4 / liters	Kg N2O / liters
2.603	*0.00013853116368*	*0.00013853116368*

Source: Adapted (EPA, 2016)

Then, the greenhouse gas emissions from biofuel are calculated using the emission factors for biofuel use in mobile sources, as shown in Table 04.

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Table 04. Emission Factors for Biodiesel from Fossil Fuel Diesel Oil

Kg CO_2 / liters	**Kg CH_4 / liters**	**Kg N_2O / liters**
2.431	*0.00033159456*	*0.0000198956736*

Source: Adapted (EPA, 2016)

Emissions in metric tons of CO_2

3. $E(t) = ECOF x\ GWP\_CO_2 + ECHF\ (t)\ x\ GWP\_CH_4 + ENOF(t)\ x\ GWP$

Where:

E(t) = Total Emissions (t CO2-e)

ECOF = CO2 Emissions (t) fossil (The sum of total fossil fuel quantity (liters or m3) x Fossil fuel emission factor (kg CO2/liter) / 1000

ECHF(t) = CH4 Emissions (t) (The sum of total commercial fuel quantity (liters or m3) x Commercial fuel emission factor (kg CH4/liter) / 1000

ENOF(t) = N2O Emissions (t) (The sum of total commercial fuel quantity (liters or m3) x Commercial fuel emission factor (kg N2O4/liter) / 1000

Emission of biogenic CO_2

4. $EB(t) = FEB\ x\ SQB$

Where:

EB(t) = Biogenic CO_2 Emissions (t CO2)

FEB = Biocombustible Emission Factor

SQB = Sum of total biocombustible quantity present in commercial gasoline, mandated by Brazilian law, in liters

In addition to CO_2 emissions, other greenhouse gases can be emitted during fuel combustion. Therefore, if it is necessary to calculate emissions of other GHGs, the use of GHG emission factors is important.

Eletric Energy

Due to the source of electric energy in Brazil mainly coming from large hydroelectric, thermal power plants, nuclear energy, and renewable energy, there is a significant monthly variation in energy sources as they complement each other in case of shortages. Therefore, monthly greenhouse gas emission factors exist (EPE, 2022).

For greater accuracy of the inventory, the calculation of greenhouse gas emissions from monthly consumed electric energy was performed. This is because the emission factors for electricity generation vary each month. These variables change every year, and the Ministry of Science and Technology provides the conversion table annually, as shown in Table 05.

Table 05 - Emission factors for electricity generation

Parameters for the 2019 Inventory	
Month	FE of SIN (tCO_2/MWh)
Jan	0.0960
Feb	0.0815
Mar	0.0815
Apr	0.0815
May	0.0815
Jun	0.0815
Jul	0.0815
Ago	0.0815
Sep	0.0815
Out	0.0815
Nov	0.0815
Dec	0.0815

Source: Adapted (EPE, 2022)

Greenhouse Gas Emission Calculation Equation for Electricity Purchase

$$E(t) = \sum_{n=1}^{\infty} \left(\frac{CEM\_jan\ x\ FEM\_jan}{1000} + \frac{CEM\_feb\ x\ FEM\_feb}{1000} + \cdots + \frac{CEM\_dec\ x\ FEM\_dec}{1000} \right)$$

Where;

EB(t) = Biogenic CO2 emissions (t CO2)

FEB = Emission Factor of the biofuel

SQB = Sum of total quantity of biofuel that exists in commercial gasoline as required by Brazilian law in litres

Calculation of Emission Source for Transportation (Logistics)

The calculation of CO2-e emissions from road transportation that utilizes greenhouse gases (GHG) for the movement of equipment, personnel, and materials for railway operation and maintenance. The calculation of carbon dioxide equivalent (CO2-e) emissions from road transportation that utilize greenhouse gases (GEE) for the movement of equipment, personnel, and materials for railway operation and maintenance is carried out by identifying the types of transportation and the types of fuels (diesel, gasoline, ethanol, natural gas, etc.) used by road vehicles. Then, the values of fossil fuel and biofuel are separated, and the emission factors for the use of fossil fuels in mobile sources are applied for GHG conversion, as per Table 06.

Table 06. Global Warming Potential (GWP) of greenhouse gases

Fuel	Unit	Emission Factors (kg GEE/un.)		
		CO_2	CH_4	N_2O
Gasolina Automotiva (pura)	litros	2,212	0,0008	0,00026
Óleo Diesel (puro)	litros	2,603	0,0001	0,00014
Gás Natural Veicular (GNV)	m³	1,999	0,0034	0,00011
Gás Liquefeito de Petróleo (GLP)	kg	2,9325	0,0029	0,00001
Querosene de Aviação	litros	2,52	0,00002	0,00007
Gasolina de Aviação	litros	2,25	0,00002	0,00006
Lubrificantes	litros	2,7175	0,0001	0,00014
Óleo Combustível	litros	3,1	0,0004	0,00002

Source: Adapted (EPA, 2016)

Then, the GEE emissions from biofuel are calculated using the emission factors for the use of biofuels in mobile sources, as per Table 07.

Table 07. Emission factors for the use of biofuels in mobile sources

Fuel	Unit	Emission Factors (kg GHG/un.)		
		CO_2	CH_4	N_2O
Etanol Hidratado	litros	1,457	0,0004	0,00001
Biodiesel (B100)	litros	2,431	0,0003	0,00002
Etanol Anidro	litros	1,526	0,0002	0,00001

Source: Adapted (EPA, 2016)

Next, the GHG emissions of CH_4 and N_2O from commercial fuel were calculated using the conversion factors of Emission Factors (converted units) for CH_4 (kg/litre) by type, year, and fleet fuel, as well as the conversion factors of Emission Factors (converted units) N_2O (kg/litre) by type, year, and fleet fuel.

Emissions in metric tons of CO_2

5. $E(t) = (ECOP x GWP\_CO_2) + (ECH (t) x GWP\_CH_4) + (ENO(t) x GWP\_N_2O)$

Where;

E(t) = Total emissions (t CO_2-e)

ECOP = Emissions of pure fossil CO2 (t) (sum of total quantity of fossil fuel (litres or m3) x Emission Factor of fossil fuel (kg CO_2 / litre) / 1000

ECH(t) = Emissions of CH_4 (t) (sum of total quantity of commercial fuel (litres or m3) x Emission Factors of commercial fuel (kg CH_4 / litre) per year, fuel, and fleet type (Table 07) / 1000

ENO(t) = Emissions of N_2O (t) (sum of total quantity of commercial fuel (litres or m3) x Emission Factors of commercial fuel (kg N_2O_4 / litre) per year, fuel, and fleet type (Table 08) / 1000

Emission of biogenic CO_2

6. EB(t) = FEB x SQB

Where;

EB(t) = Biogenic CO2 emissions (t CO2)

FEB = Emission factor of the biofuel

SQB = Sum of total quantity of biofuel that exists in commercial gasoline as required by Brazilian law in liters

3. Case Study: Northeast Brazil

3.1. Raw material production, transportation, and on-site construction

The structure of urban railway transportation in the Northeast of Brazil dates back more than 150 years, as the Brazilian government strategically chose to repurpose the inactive freight railway to build the urban railway. Therefore, there is no real information available about the construction of the urban railway in the Northeast of Brazil. Due to this reason, the inventory of greenhouse gas emissions (GHG) from the construction of the railway is not discussed in this case study.

Based on other studies like the article "Calculation of life-cycle greenhouse gas emissions of urban rail transit systems: A case study of Shanghai Metro"(Li et al., 2018b) the emissions from the construction of a railway track represent less than 5% of the entire lifecycle of a railway system. Therefore, the lack of construction data does not have a significant impact on the inventory.

3.2. Operation and maintenance

The energy consumption of the operation and maintenance phases can be divided into eight sources: Fugitive emissions, station energy and lighting, electric line traction, diesel line traction, base energy and lighting (workshop and administration), control center energy and lighting, transportation and materials (Lazzerini et al., 2016, Hausberger et al., 2023, Disney et al., 2018, Bates and Jablonski, 2007). To serve as a reference for future life cycle assessment (LCA) studies on urban railway transportation systems, the scope of each source is described below:

Table 08. Building Energy Consumption Data

	Energy Consumption	Emisions (t CO2e)	CO_2 -biomass
Eletric (building)	9455.21	700.60	-

Table 09. Logistic Transportation Energy Consumption Data

	Energy Consumption	Emisions (t CO2e)	CO_2 -biomass
Diesel	30923	11.23	11.23
Gasolina	86472	184.31	45.05

Table 10. Gases Released by Air Conditioning and Fire Extinguisher

	Energy Consumption	Emisions (t CO2e)	CO_2 -biomass
Emision fugitive	1397.98	1035.45	-

Table 11. Train Traction Energy Data (Electric)

	Energy Consumption	**Emisions (t CO2e)**	**CO_2 -biomass**
Eletric (tracion)	51663.668	3774.70	-

Table 12. Train Traction Energy Data (Diesel)

	Energy Consumption	**Emisions (t CO2e)**	**CO_2 -biomass**
VLT (diesel)	1978746	5648.34	555.20

Considering data availability and accessibility, the year 2022 was chosen as the base year to estimate the overall emission level of the operation and maintenance phases. According to data obtained from the Brazilian urban train company, the total energy used in station and building energy is presented in Table 08 along with associated emissions. The total energy and resources consumed in logistic transportation with car and truck entries and exits are presented in Table 09 along with associated emissions. In Table 10, I summarize all the air conditioning gases and fire extinguishers used in the railway system in 2022, along with associated emissions. Tables 11 and 12 provide the traction energy consumption for electric and diesel trains, respectively. This traction energy represents around 83% of the greenhouse gas emission (GHE) of the railway system, as shown in Figure 2.

Since the railway system in the northeastern region of Brazil relies significantly on diesel-powered trains, the emission from electric energy does not constitute the majority of emissions, in contrast to most other railway systems globally, which are predominantly powered by electricity, as demonstrated in Figure 3.

Figure 3. Composition of consumption and emissions in 2021.

Although the emissions are not directly originated from electricity consumption during operation, Life Cycle Assessment (LCA) calculations incorporated greenhouse gas (GHG) emissions from the processes of electricity generation and transmission. In the year 2022, the average annual electricity consumed for powering trains in the northeastern Brazilian railway system during the operation phase amounted to 51.7 million kWh. The GHG emissions from the electricity used to power the trains were calculated to be 3,774.70 metric tons of CO2 equivalent (tCO2e).

In the same year, the diesel-powered train system consumed 1,978,746 liters of diesel fuel for its operation. The GHG emissions resulting from this consumption were calculated to be 5,703.54 metric tons of CO2e.

By adding emissions from other energy resources, the total annual GHG emissions from operation and maintenance activities amounted to 11,996.11 metric tons of CO2e.

Considering a service period of 50 years, the total GHG emissions over the life cycle of operation and maintenance activities for the northeastern Brazilian railway system were estimated to be a total of 59,980,550 metric tons of CO2e.

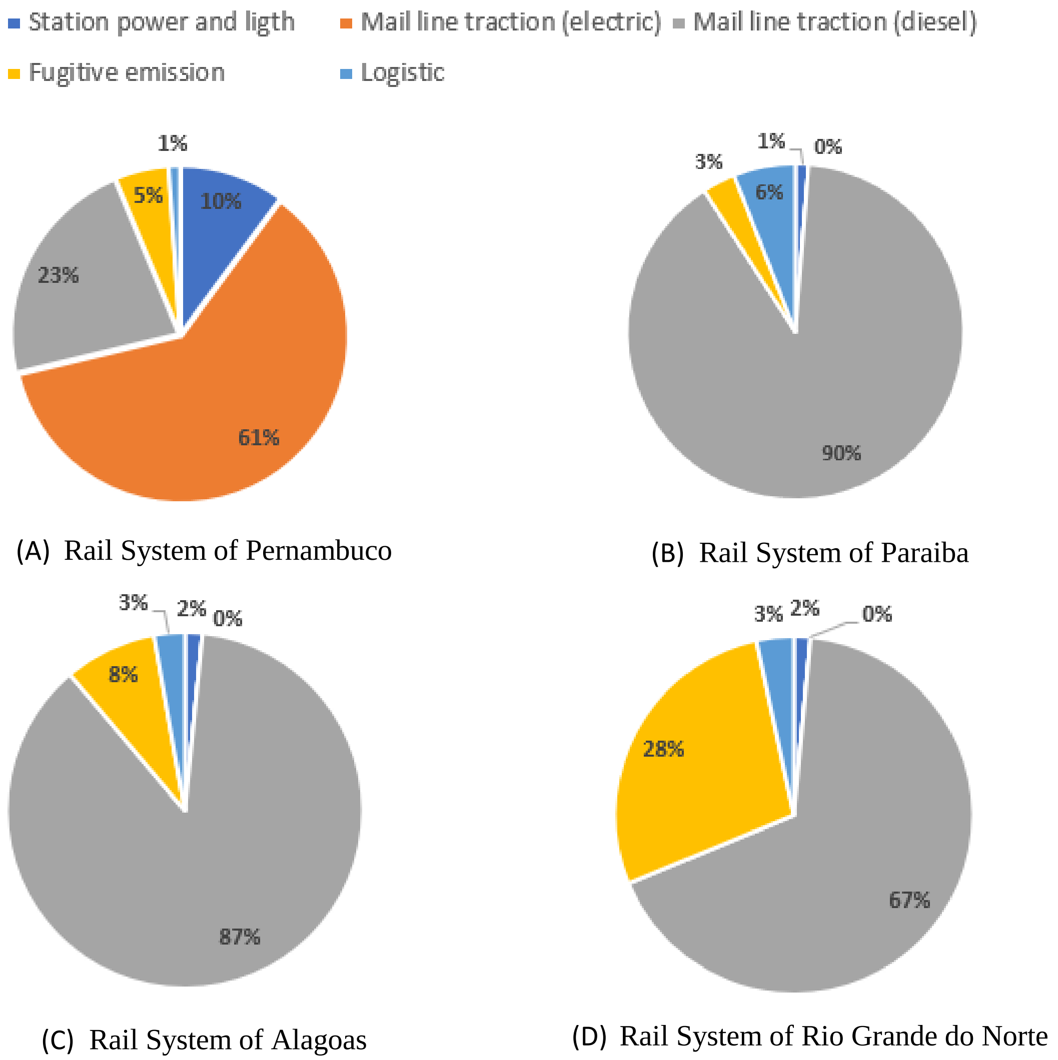

Figure 4. Composition of consumption and GHG emissions.

The provided data on greenhouse gas (GHG) emissions in the states of Pernambuco, Paraiba, Alagoas, and Rio Grande do Norte, as shown in Figure 4, presents an interesting view of the different emission sources associated with railway operations and related infrastructure.

It's evident that GHG emissions vary considerably among the states and between different emission sources. The "Main line traction" category is a prominent source of GHG emissions, both for electric and diesel traction systems. In Pernambuco, for example, electric traction significantly contributes to emissions as the trains are powered by both electric and diesel energy, while in Paraiba, Alagoas, and Rio Grande do Norte, diesel traction is the main source due to the use of diesel-powered light rail vehicles. Emissions from diesel traction can be impacted by factors such as engine efficiency and fleet composition (Qi et al., 2019, Chu et al., 2015, Chang et al., 2019, Ramos da Silva et al., 2023, Jackson and Brander, 2019, Mao et al., 2015).

In summary, these data provide a valuable starting point for assessing GHG emissions associated with railway operations in different cities. They highlight the need for a comprehensive and context-specific approach to addressing emissions, considering local sources and challenges. By focusing on clean technologies, operational efficiency, and strategic planning, it's possible to significantly reduce GHG emissions in these railway operations.

The comparison between states demonstrates the diversity of energy choices for train traction. While Pernambuco opted for electric traction and thus records high emissions associated with electricity consumption, Paraiba, Alagoas, and Rio Grande do Norte rely more on diesel traction, reflecting emissions from this fossil fuel. Besides CO2, diesel combustion also emits fine particles like soot. These particles not only impact air quality but can also absorb solar radiation and affect the climate (Fan et al., 2016, Li et al., 2015, Shao et al., 2005, Zhang et al., 2013, Kuti et al., 2013, Zheng et al., 2011). The burning of diesel also releases nitrogen oxides (NOx), which contribute to the formation of acid rain and tropospheric ozone (a component of smog). Tropospheric ozone is a pollutant and a short-lived greenhouse gas (GHG) (Zare et al., 2021, Mohamed Ibrahim et al., 2015, Krasinski and Gradon, 2016, Liu et al., 2015, Alcántara-Carmona et al., 2017, Song et al., 2006, Ferrari and Salvo, 2017, Gong et al., 2013).

For the railway systems in the states of Paraiba, Alagoas, and Rio Grande do Norte, which predominantly use diesel traction, the implementation of emission reduction technologies like diesel oxidation catalysts and selective catalytic reduction (SCR) systems help minimize NOx and particulate emissions (Donnici et al., 2014, Shin et al., 2014, Puig-Samper Naranjo et al., 2021, Li et al., 2018a, Zhang et al., 2017b, Mohamed Ibrahim et al., 2015). More efficient engines and fuels with lower sulfur content also contribute to emissions reduction (Mohamed Ibrahim et al., 2015, Ferrari et al., 2018, Gong et al., 2013, Liu et al., 2005, Matsumoto, 2009). Transitioning to cleaner energy sources such as electrification (electric vehicles), renewable fuels like biodiesel (Thongchai and Lim, 2018, Thongchai and Lim, 2020, Vargas et al., 2019) and hydrogen technologies (Fang et al., 2014, Fernández-Ríos et al., 2022, Ibrahim and Ramesh, 2013, Ciancetta et al., 2019), is essential to reduce GHG emissions from the railway systems in these states.

Emissions from station power and lighting are factors to consider in all cities. While these emissions may seem smaller compared to traction emissions, they contribute to the overall emission profile of the region.

The "Logistics" category underscores the importance of emissions related to the transport of equipment, personnel, and materials needed for railway operation and maintenance. This highlights the relevance of logistic efficiency to reduce total emissions. The energy efficiency of vehicles and logistics operations used for transporting railway system materials in this region should have a more efficient system to consume less fuel and, thus, emit fewer GHGs per unit of transported load (Okyere et al., 2018, Perez-Martinez et al., 2020).

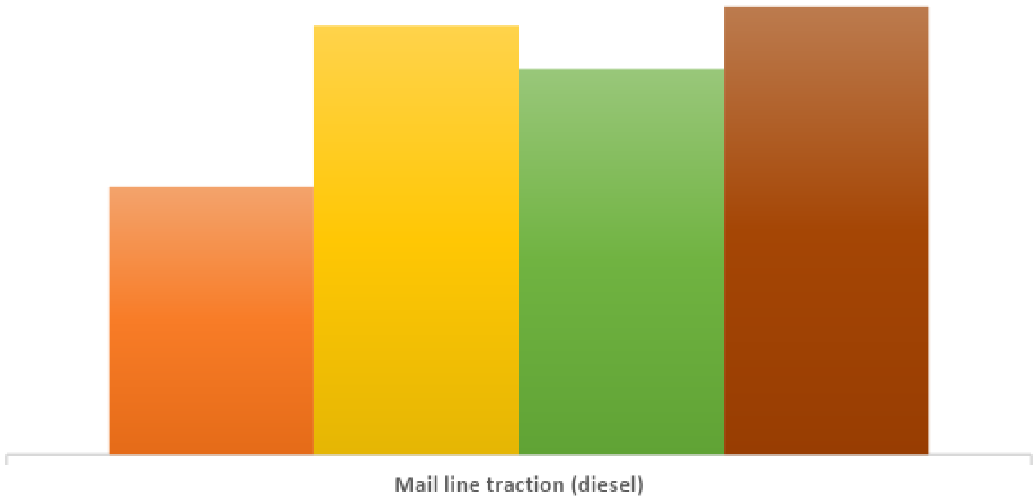

Figure 5. GHG emissions of main line traction (diesel)

The provided data on greenhouse gas emissions (GHG) from diesel traction in different railway states in the northeast - Paraiba, Alagoas, Rio Grande do Norte, and Pernambuco, in Figure 5 are essential for understanding the environmental impact of these transportation systems and can serve as a basis for formulating more effective environmental policies in the railway transportation systems of these regions (Holler Branco et al., 2022, Holian and Kahn, 2015, Wen and Wang, 2022).

The quantities of GHG emissions associated with diesel traction vary significantly among the mentioned states. Pernambuco has the highest emissions, followed by Alagoas, Rio Grande do Norte, and Paraiba. This variation is influenced by various factors, such as the length of routes where Paraiba has a longer route than the other regions, and the volume of railway traffic which is higher in Pernambuco due to its status as a major metropolitan area in the northeast of Brazil. The energy efficiency of the trains is not a factor since all the light rail vehicles used in this region have the same technology and were manufactured by the same factory. An important factor that could also lead to higher emissions between states is the topography of the region; factors like curves and inclines, among others, could increase GHG emissions (Wen and Wang, 2022). However, this work will not conduct an in-depth study of these factors, as this is one of the limitations of this research.

3.3. Dismantling and Recycling

Urban railway transportation was developed relatively late in the Northeast of Brazil, with the opening of the first system in 1985 through repurposing some trains from the existing railway network and the acquisition of new ones. Currently, there is no real data available regarding the dismantling and recycling of urban railway transportation infrastructure in the Northeast of Brazil. As a result, dismantling is not discussed in this case study.

4. Discussion

4.1. Comparative System

This study aims to emphasize the importance of a comparative analysis of traction emissions, station operations, and infrastructure in different urban railway transport systems around the world. It's important to note that the availability of related studies is limited, and the comparative analysis is conducted within the same scope whenever possible, referencing data and information found in specialized literature and various case studies with varying local parameters.

In this study, the greenhouse gas (GHG) emissions of urban railway transport systems in Northeast Brazil, Shanghai Metro, Delhi Metro, and the California corridor (San Diego to Los Angeles, San Francisco, and Sacramento) were compared. Furthermore, the reasons for the differences in data between these regions were explored. To facilitate the comparison, the emission intensities of each city were standardized per passenger-kilometer traveled (PKT).

This comparative analysis allowed for the identification of variations in GHG emissions among different urban railway transport systems. The differences can be attributed to factors such as the energy source used, train energy efficiency, population density, transport demand profile, and specific infrastructure of each city. This information is valuable for understanding sustainable transportation practices and policies and can provide insights to enhance efficiency and reduce emissions in railway systems (Da Fonseca-Soares et al., 2023).

By standardizing emission intensities per PKT, fairer comparisons can be made and areas for improvement in each railway system can be identified. This approach considers both the number of passengers transported and the distance traveled, enabling a more equitable assessment of environmental performance (Chang et al., 2019).

Therefore, this comparison of emissions standardized per PKT in different urban railway systems provides an important view of disparities and offers valuable information for the development of more sustainable and emission-efficient transportation strategies.

In 2012, the total GHG emissions generated from electricity consumption for traction in Shanghai amounted to 637,011.3 tCO2e. Based on a total passenger volume of approximately

2.3 billion passengers and an average driving distance of 12.0 km, the traction emissions were 23.4 g CO2e/PKT. The total traction emissions in 2011 in Delhi were 232,161.7 tCO2e, with a total passenger volume of 651 million passengers (Doll and Balaban, 2013). Hence, the traction emissions in Delhi were 24.3 g CO2e/PKT. The traction emissions of Heavy Rail Transit (HRT) in the California corridor in 2009 were 31.8 g CO2e/PKT (Chang and Kendall, 2011a). Hence, the traction emissions in Delhi were 24.3 g CO2e/PKT. The traction emissions of Heavy Rail Transit (HRT) in the California corridor in 2009 were 31.8 g CO2e/PKT (Chang and Kendall, 2011a). By comparison, Brazil's rail system in 2022 had rail transport traction emissions of 9.5 tCO2e with a total passenger volume of approximately 2,316,000 passengers over an average distance of 194 km with 21.14 gCO2e/PKT.

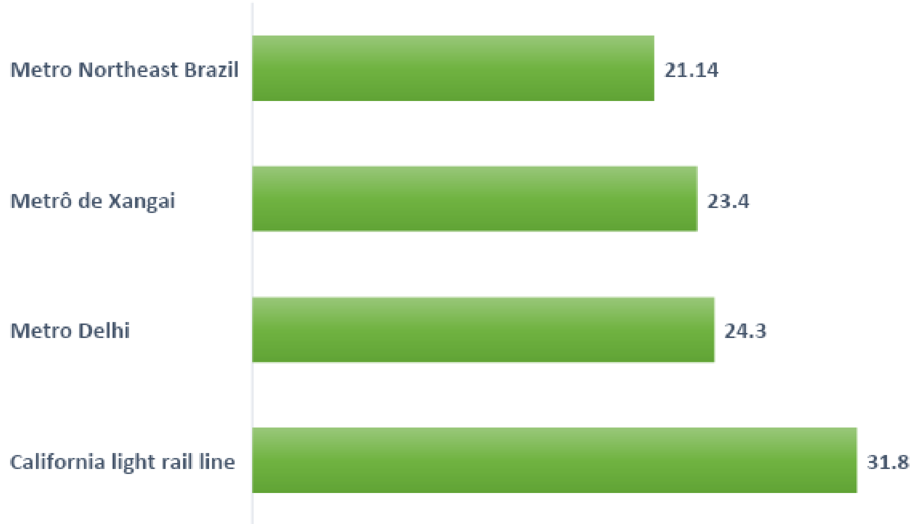

Figure 6. GHG emission (gCO2/PKT).

The comparison of greenhouse gas (GHG) emissions per passenger-kilometer (gCO2/PKT) among different railway transport systems provides valuable insights into the environmental efficiency of these systems in different regions of the world (Li et al., 2018b).

Figure 6 depicts the variation in emissions among railway transport systems in different world regions. This suggests that factors such as energy source, system efficiency, population density, and other local aspects have a significant impact on emissions associated with railway transportation.

The comparison of gCO2/PKT values indicates that metro systems tend to be more emissions-efficient than light rail systems. This difference can be attributed to variations in technology used, vehicle capacity, and electrification systems, such as the use of fossil energy for traction in certain trains, as in the case of the Northeast of Brazil.

It's interesting to note that despite regional differences, Delhi and Shanghai metro systems exhibit similar gCO_2/PKT values. This might suggest that both systems are adopting similar strategies to reduce emissions, such as electrification and the adoption of more efficient technologies.

Additionally, metro systems like Delhi and Shanghai, which likely have more extensive electrification systems, present lower emissions. This underscores the importance of electrification in emissions reduction and promoting sustainability in railway systems.

There are several factors that can influence GHG emissions, such as the number of train cars, the type of traction energy (which can vary based on the country's energy matrix), infrastructure, urban development, and geographical characteristics of the region among others. These factors were not extensively studied in this article, serving as limitations to this research.

The gCO_2/PKT values can also be influenced by local context, including the availability of renewable energy sources, sustainable transportation policies, and investments in infrastructure.

4.2. Mitigation of GHG Emissions

The mitigation of greenhouse gas (GHG) emissions in the railway system is a topic of great relevance in the context of environmental concerns and emission reduction goals. Based on recently published articles, several promising approaches and strategies to mitigate GHG emissions in the railway sector can be observed.

Electrification of railway lines has been highlighted as one of the main strategies to reduce GHG emissions (Ramos da Silva et al., 2023, Chen et al., 2019), In the case of the railway system in Northeast Brazil, which consists of both electric and diesel parts, transitioning diesel-powered trains to electric trains powered by renewable energy sources such as solar energy installed on train rooftops to reduce traction electric energy consumption (Carneiro and Soares, 2020) or wind energy has demonstrated effectiveness in significantly reducing carbon emissions. Additionally, the use of batteries and energy storage systems can enable the use of clean energy even on non-electrified sections (Gee and Dunn, 2015, Zhu et al., 2020, Khodaparastan et al., 2019, Zhu et al., 2021a, Krueger et al., 2021).

Research and development of technologies that improve train efficiency can directly result in GHG emission reduction. Lighter trains (Kimball et al., 2013, Dalkic et al., 2017), aerodynamic designs, and energy recovery systems (Soffker and Gralla, 2016, Zhu et al., 2021a, Krueger et al., 2021) can minimize fuel consumption and, consequently, carbon emissions.

Implementation of intelligent traffic and operation management systems (Masirin et al., 2017) can optimize train flow, reducing the need for sudden stops and accelerations. This not only saves energy but also contributes to more efficient and lower-emission operations.

Investments in maintenance and modernization of railway infrastructure can result in smoother tracks, reducing train friction and energy consumption, or even utilizing friction for energy recycling (Mayba and Glazunov, 2020, Gerlici et al., 2017, Cui et al., 2021, Sánchez et al., 2019) Additionally, modernizing stations and signaling systems can improve operational efficiency (Gassner et al., 2018, Perez-Martinez et al., 2020).

Adoption of emission reduction technologies, such as exhaust gas purification systems and particle filters, can contribute to the reduction of emissions in diesel-powered trains. These technologies can minimize the emission of harmful air pollutants.

Integration between different modes of transportation, such as rail, buses, and bicycles, can reduce the dependency on private vehicles and, consequently, GHG emissions.

Urban planning focused on accessibility, such as research evaluating accessibility in high-speed metro systems and light rail vehicles with wheelchair accessibility in public transport, can encourage more people to adopt low-emission transportation modes (Yao et al., 2016, Bonotti et al., 2015, Moyano et al., 2018, Liu et al., 2021, Janic, 2011, Hong et al., 2020, Ferreira et al., 2021).

Empowering operators and maintenance personnel with sustainable and efficient practices can also contribute to emission reduction (Carneiro et al., 2022). Economical driving techniques and proper train maintenance can optimize energy consumption (Merchan et al., 2020).

5. Conclusion

This research aimed to calculate greenhouse gas (GHG) emissions throughout the lifecycle of the railway system in the Northeast of Brazil, based on observed real data. Additionally, a comparative analysis was conducted with the global context to understand the emission levels of urban railway transport systems.

The results obtained revealed that the total GHG emissions over the lifecycle, considering the construction length of the entire railway system in Northeast Brazil, were 11,996.11 metric tons of CO2 equivalent (tCO2e). Taking into account a lifespan of 50 years, projected emissions are estimated to be 59,980,550 tCO2e.

These results provide an important understanding of the environmental impact of the railway system in Northeast Brazil and serve as a basis to identify areas for improvement and guide future actions towards reducing GHG emissions in this context.

As the railway system in the Northeast has been in operation for over 150 years, utilizing the cargo transport system of the Brazilian federal railway network, there are no concrete construction material quantity data available, making it impossible to calculate construction-phase GHG emissions.

The Brazilian urban railway system differs from the rest of the world, as a significant portion of the system is still diesel-powered. Nevertheless, when comparing the operation and maintenance phase emissions, the traction emissions of the Brazilian Northeast system were 21.14 gCO2e/passenger-km, which were competitive with those of the Delhi Metro and the California High-Speed Rail corridor, based on a much larger passenger volume in Shanghai. However, there was still significant potential for energy savings in the operation phase, especially in stations designed to be excessively grandiose and ornamented with energy-intensive facilities. A more reasonable ventilation structure for metro stations and energy-saving lighting, such as LED lights, can effectively reduce their emissions.

For future research, it is recommended that a more detailed comparative analysis be conducted, considering system boundaries, greenhouse gas (GHG) emissions accounting methods, and datasets from different case studies. This approach will allow for a more comprehensive and accurate understanding of emissions in different contexts.

Furthermore, the development of a more comprehensive estimation tool and an applicable reference standard for various areas, equipment types, structures, and techniques would be highly beneficial. This would facilitate the collection and analysis of consistent and comparable data, enabling a more accurate assessment of GHG emissions in different railway systems.

The railway sector, as part of the transportation sector, plays a significant role in meeting environmental and emissions reduction targets set by various governments and international agreements. Awareness of emissions associated with diesel traction is crucial to guide sustainability policies and efforts.

The analysis of such data can serve as a basis for formulating more effective environmental policies in the railway transport systems of these regions. Awareness of predominant emission sources in each city can guide efforts to mitigate environmental impact.

Data like these can highlight the importance of transitioning to cleaner energy sources, such as electrification of railway traction, adoption of low-carbon biofuels, installation of photovoltaic energy, improvements in railway infrastructure, and sustainable stations to reduce the environmental impact of railway transport.

In summary, the analysis of GHG emissions data in railways provides valuable insights for sustainability-oriented decision-making. These insights can steer investments towards cleaner technologies, efficient transportation strategies, and collaborations between the public and private sectors to achieve environmental goals and reduce the carbon footprint of railway transport.

CHAPTER 05

AN APPROACH FOR WATER AND ENERGY SAVINGS IN PUBLIC BUILDINGS: A CASE STUDY OF BRAZILIAN RAIL COMPANY

The results presented in this chapter were published in the journal *Sustainability* (ISSN: 2071-1050)
Journal Rank Europe: JCR 3.9; CiteScore 5.8 - Q2 (*Environmental Studies*) /Q1 (*Geography, Planning and Development*)
Journal Rank Brazil: A2 (*Environmental Studies*) / A2 (*Engineering I*)

1. Introduction

Humans are using more natural resources every day, which raises concerns about how their consumption influences the emissions of polluting gases into the atmosphere and how the waste generated by their activities might be directly linked to climate change. Consumption of goods and services in large urban areas demands more natural resources as the population grows (Gassner et al., 2018).

Water scarcity is a current problem in many parts of the planet and there is a worldwide concern about water availability to meet future water demand. Overall, from 2016 to 2050, the global urban water shortage is expected to worsen significantly. Moreover, nearly half of the world's urban population (1.693–2.373 billion people) is expected to reside in a water-scarce region by 2050 (He et al., 2021). Engineering and infrastructure have traditionally been used to alleviate urban water shortages, however, water infrastructure is expensive and has the potential to cause environmental consequences (He et al., 2021).

Water scarcity is related to energy shortage. For the safe and reliable generation of electricity, the power generation industry requires large amounts of water, from moving turbines in the case of hydroelectric or to condensing steam in the case of thermoelectric (Sanders, 2015). In countries like Brazil, where most of the electricity is produced by hydroelectric power plants, water scarcity directly impacts energy production.

The implementation of actions for sustainable use of water and energy is critical for mitigating water and energy supply problems. Demand-side management (DSM) is one of these efforts, and consists of planning and conducting water or energy consumption activities to encourage consumers to change their use levels and patterns (Gellings, 2017). Furthermore, DSM programs are designed to minimize consumption by supporting high-efficiency technology and building design (Boshell and Veloza, 2008). Technological tools have been reported to achieve a 35-50% of reduction in water consumption in household appliances (Inman and Jeffrey, 2006).

Most literature reports the application of DSM programs to reduce water and energy consumption in schools (Flores and Ghisi, 2022, Antunes and Ghisi, 2020, Meron and Meir, 2017, Katsaprakakis and Zidianakis, 2017), universities (Khoshbakht et al., 2018, Fonseca et al., 2018), hotels (Tirado et al., 2019), and households (Lee et al., 2011).

The lack of knowledge has been considered a hindrance in implementing sustainable specifications for public buildings [8].

Another effort is the development of regulations, which are being created and updated in both developed and developing nations to obtain optimum energy savings in buildings. Building certification is a key technique for making these laws and regulations effective (Lopes et al., 2016), such as LEED, BREEAM, VERDE, and LiderA (Polli, 2020). In Brazil, the MPOG Normative Instruction of January 19th, 2010, established environmental sustainability criteria in the acquisition of goods, contracting of services or works by the Federal Public Administration (Ministério do Planejamento); and, later, Decree No. 7,746, of June 5th, 2012 (Presidência da República), established sustainable criteria, practices, and guidelines for hiring carried out by the federal public administration as legal frameworks for the adoption of criteria to reduce energy consumption and water consumption.

Strategies to promote water and energy savings may reflect in the reduction of carbon dioxide emissions (Lopes et al., 2016). The water-energy nexus is directly related and impacted by CO2 emissions and its climate consequences, which calls to a broader approach: energy-carbon-water nexus (Li et al., 2020).

The shift to a more carbon-efficient global energy system could help us achieve such goals. Buildings in particular account for 40% of energy usage, and there is significant room for reduction (European Union, 2012). In order to understand the true impacts of these emissions, it is necessary to know how goods and services are consumed by society and to measure the impacts they cause. Moreover, the current energy crises observed in Europe reinforces the need for solution on improving energy consumption efficiency and expanding energy matrix.

In this context, the Sustainable Water and Energy Consumption (SWEC) Program was developed based on demand-side management (DSM) methodologies to create a water and energy approach for sustainable consumption in public buildings. The SWEC methodology consisted of social efforts such as educational programs and user awareness, as well as technological measures such as the replacement of conventional equipment and using alternative water and energy sources. Recently, it was observed that the sustainability field are understudied in railway research (Da Fonseca-Soares et al., 2022a). Hence, this paper shows the main finding of the SWEC Program implemented in the buildings of a public railway company in Brazil.

2. Materials and Methods

2.1. SWEC validation – case study

The SWEC validation was carried out at a public company of light railway operation and maintenance. The company buildings were distributed in four different municipalities of Northeastern Brazil, as shown in Fig 1: João Pessoa, Cabedelo, Santa Rita, and Bayeux. The system is composed of 12 train stations distributed through 30 km of the railway. The main office, where most of the employee's works, is in the João Pessoa Rail Station (7o06´54"S, 34o53´26"W), while the workshop where the train maintenance is performed is located in the Cabedelo Rail Station. The company possess a total of 17 hydrometers and 22-electricity meters distributed through the buildings. The main office consumes most of the energy and water in the company (>90%), followed by train workshop and train station.

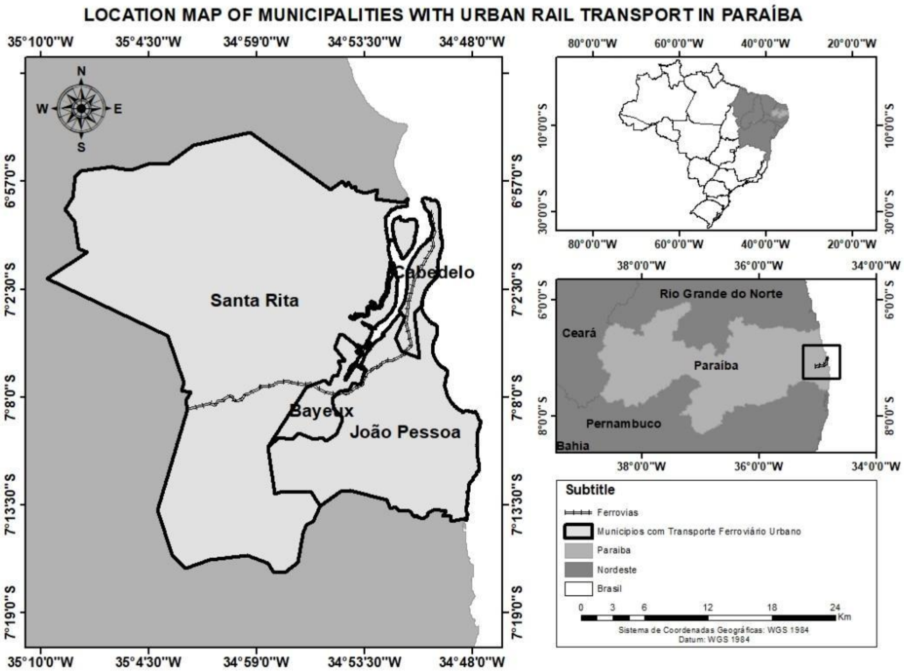

Figure 1. Location map of the Paraiba Railway System, Brazil (adapted from (Carneiro and da Fonseca Soares, 2020))

2.2 Sustainable Water and Energy Consumption Program overview

The SWEC Program aims to promote i) the sustainable usage of energy and water, ii) the reduction of resource waste; iii) optimization of water and energy expenses and iv) user conscientization. The specific goals are shown in Table 1.

Table 1. Specific goals of the Sustainable Water and Energy Consumption Program

Water	Energy
Reduce water loss and waste	Reduce energy consumption and consequently expenses with electricity
Reduce consumption, and consequently, expenses on drinking water supply	Replace inefficient equipment
Keep a reduced consumption profile over time	
Implement a structured water use management system	
Make users aware of the sustainable use of water to reduce waste from misuse	
Apply new tools and technologies for intelligent and efficient use of water	

The following sections will detail the SWEC Program framework, which consists of actions divided into four sections: a) users conscientization, b) consumption diagnosis, c) indicators for evaluating water and energy consumption, and d) evaluation of implementing alternative cleaner water and energy sources.

2.3 Sustainable Water and Energy Consumption (SWEC) Program framework

2.3.1. Users conscientization and consumption diagnosis

Previous research and other studies (Lee and Tansel, 2013, Tortajada et al., 2019, Martínez-Espiñeira and García-Valiñas, 2013) have reported on the impact of water usage behaviors on water savings. Interventions such as workshops, e-mails, signs on washrooms, posters and hand-delivered booklet have been shown to reduce water consumption by up to 35% (Ehret et al., 2020). A marketing campaign was developed to raise users' awareness. The initiative had four major components: i) reminder signs, ii) an educational booklet, iii) periodic reports, and iv) informative talks.

The reminder signs were placed on all faucets to encourage water conservation, and on all light switches to remind users to turn off the lights before leaving the room. Furthermore, signs were placed around the buildings requesting that water leaks and other maintenance issues regarding water and energy use be reported.

A printed educational booklet containing information on smarter water and energy-saving practices was delivered to all employees. Following the program's launching, bi-monthly updates on water and energy consumption and expenses were sent by institutional e-mail to supervisors and managers. The informative talks were placed during key events such as "Safety and Environmental Week" which included contests and the distribution of gifts and prizes.

For the consumption diagnosis, a database was created to gather information on water and energy use, costs, and consuming items. Table 2 lists the sources for each kind of information.

Table 2. Sources of information for water and energy consumption diagnosis

Category	Source
Consumption	24 months water and energy bills, hydrometer, and electricity meter
Expenses	24 months of water and energy bills
Consuming components	Inventory of goods and on-site inspections

2.3.2 Indicators for evaluating water and energy consumption

Indicators were set to monitor the SWEC Program results. The indicator for water and energy are displayed in Table 3.

Table 3. Indicators for water and energy consumption

Indicator	Description
W1 –Global consumption of water (m3)	Volume of piped water consumed by all buildings
W2 – Local consumption (m3)	Volume of piped water consumed by each building
W3 – Self-closing faucet (%)	Number of self-closing faucet divided by the total number of faucets
W4 – Leaking hydraulic components (%)	Number of leaking items divided by the total number of hydraulic items
W5 – Per capita water consumption (m3 /employee)	Water consumed per employee
E1 – Global consumption of	Electricity consumed by all buildings

electricity (kWh)	
E2 – Local consumption of electricity (kWh)	Electricity consumed by each building
E3 – LED lighting (%)	Number of LED lightning divided by the total number of lightning
E4 – Per capita electricity consumption (kWh/employee)	Electricity consumed divided by the number of employees

The indicators W5 and E4 were included in the Program after observing an increment in the number of employees in the company of 15% in the first year. The addition of W3 was justified by the findings by other studies that more than 50% of water saving is possible by changing the type of faucet (Englart and Jedlikowski, 2019). In addition, a study conducted in a hotel in Spain showed that installing water-saving devices in the taps is highly profitable (Barberán et al., 2013).

The frequency of data collection for each indicator was defined as follows: monthly for W1, W2, W5, E1, E2, and E4, which the primary source of information is the monthly bills of the concessionaires; biannual for W3, W4 and E3, whose main source of information is on-site inspections of all buildings. The frequency of data collection can be flexible depending upon the needs and resources available for implementing the Program.

On-site inspections were carried out to identify, count, and examine the state of all water and energy consumption items. The surveys were conducted with peers every 6 months, although a higher frequency can improve the results by fast detecting issues.

2.3.3 Clean alternative energy and alternative water supplies

The SWEC Program´s technological efforts also included the installation of greener sources of water and energy. Given the local characteristics of 5.82 kWh m-2 average global radiation (Melquíades et al., 2022) and annual average precipitation of 1914 mm, the acquisition of a photovoltaic system for alternative energy and rainwater harvesting for non-contact uses water supply was suitable to meet the goal of reducing water and energy cost, particularly through more sustainable sources.

3. Results and discussion

3.1. First 24-months results

Table 4 shows the results of a SWOT analysis conducted to evaluate the SWEC Program´s implementation in the company.

Table 4. SWOT analysis of SWEC Program implementation in the building of a public railway company in Northeastern Brazil.

S – strengths	**W – Weakness**
High potential of cost reduction with water and energy	Manpower shortage for the company´s buildings maintenance
Demands are concentrated in a few key buildings of the company, facilitating the monitoring of the Program	Absence of scheduled maintenance of the hydraulic and electrical networks
Alignment of the program with the company´s strategic planning	Risk of low adherence to the Program by the staff
Increase the quality of life at work through the application of modern devices and technologies	
O – Opportunities	T - Threats
Change of conventional tariff modality in the Workshop facility for the horo-seasonal model	Tariff adjustment of water and energy concessionaires
The public impression of rational water and energy use	Energy and water deviation
Brazilian government cost-cutting measures	Vandalism in water and energy consuming items (e.g. lightings, faucets, flushing, etc.)
Environmental legislative changes and sustainable bidding demand for the Public Administration	

Table 5 presents the summary of the indicator’s performance after the first 24-months of Sustainable Water and Energy Consumption Program in the public company of light railway in Northeastern Brazil.

Table 5. Summary of the results for each indicator after 24-months of implementation

Indicator	Main Results
W1 –Global consumption of water (m3)	Increased 37%, from 562.5 to 771.5 m3
W2 – Local consumption (m3)	-
W3 – Self-closing faucet (%)	Did not suffer any variation.
W4 – Leaking hydraulic components (%)	Increased from 7% to 9%.
W5 – Per capita water consumption (m3 /employee)	Reduced 10%.
E1 – Global consumption of electricity (kWh)	Reduced 11.2%.
E2 – Local consumption of electricity (kWh)	-
E3 – LED lighting (%)	Increased from 20% to 27%.
E4 – Per capita electricity consumption (kWh/employee)	Reduced 19%, from 184 kWh to 150 kWh.

The global water consumption, W1, increased significantly while the global energy consumption, E1, decreased. The increase in water consumption may be justified by the following reasons: the company had an increase in manpower of 15% during the period, the maintenance and replacement of hydrometers which were broken or not properly reading the real water consumption, and the water theft from the company in remote areas considering the economic crises and the number of unemployment in Brazil in the last years (Pereira and Cabral, 2019).

As seen in Table 5, the reduction per capita energy consumption, E4, was greater than per capita water consumption, W5. This may be justified by the fact that, in addition to user´s conscientization actions, more efficient electrical items, such as air-conditioning with inverter technology and LED lightings were substituted (E3). In Israel, some green schools were defined in research and as having particularly low usage in buildings that had a very efficient air conditioning system (VRF) installed (Meron and Meir, 2017). It was observed that this strategy consumed approximately 41% less energy per year than the educational systems.

Only via user´s education and corrective maintenance of hydraulic items it was possible to reduce per capita water consumption by 10%. Unfortunately, it was not possible to acquire more efficient hydraulic equipment such as self-closing faucet (W3) or dual flushing toilets kits. For W2 the Poco station highlighted with a observed reduction of 77%, attributed to a leaking fixture in the toilet flush.

During the on-site inspection it was detected that some water-consuming items such as flushes, and faucets were broken or showed some defect that limited their use. As a results of the SWEC Program´s application, these items were repaired or substitute by maintenance staff and consequently the number of water consuming items increased. The slightly increase in the leaking hydraulic components, W4, can be justified by the fact that past defective items, which have since been repaired, were susceptible to leaking from misusage or minimal maintenance. The W4 results clearly indicate that greater attention should be spent towards maintenance of consuming items, as their leakage might represent a large amount of water wasted daily, reducing the overall Program efficiency for water saving. Water waste in public buildings has been identified as a serious issue in public buildings as a result of faulty plumbing fixtures (Roccaro et al., 2011).

After 18 months, employees were given a questionnaire, and the following results were obtained: 97% agree totally or partially with the importance of acquiring more efficient equipment, 88.7% declares, wherever feasible, act to reduce water consumption, and 93% care about sustainable water consumption.

Water conservation education and awareness initiatives, as well as the marketing of water-saving devices, have a significant influence on water use (Tortajada et al., 2019). To improve user’s conscientization, it would be highly recommended the creation of a social media campaign which were proven to turn marketing campaigns much more powerful (Ketter and Avraham, 2012).

Given that rainwater acceptability is higher for non-contact and non-intake uses (Takagi et al., 2019), the SWEC Program proposed rainwater usage for gardening, trains washing and toilet flushing. It was found that for the mentioned usage, the economic viability of the system would be met (Andrade, 2019a). However, it was not possible to be executed due to administration restrictions. Moreover, a study conducted in Recife (a city nearby Joao Pessoa) showed that green roofs have also a great potential for non-potable uses and should be considering in buildings to reduce consumption of public supply water (Santana et al., 2022).

3.2. Recent results

One of the main results of the SWEC Program was achieved some years after two years, by the installation of two on-grid photovoltaic (PV) systems: a) a PV system of 67kWp in João Pessoa office, and b) a PV system of 29.5kWp in Cabedelo workshop. Fig. 2. shows the PV system installed in Joao Pessoa office. The simple payback period was expected to be four years. This estimative was based on the PV system prices in the region, insulation hours in the area and the electricity prices.

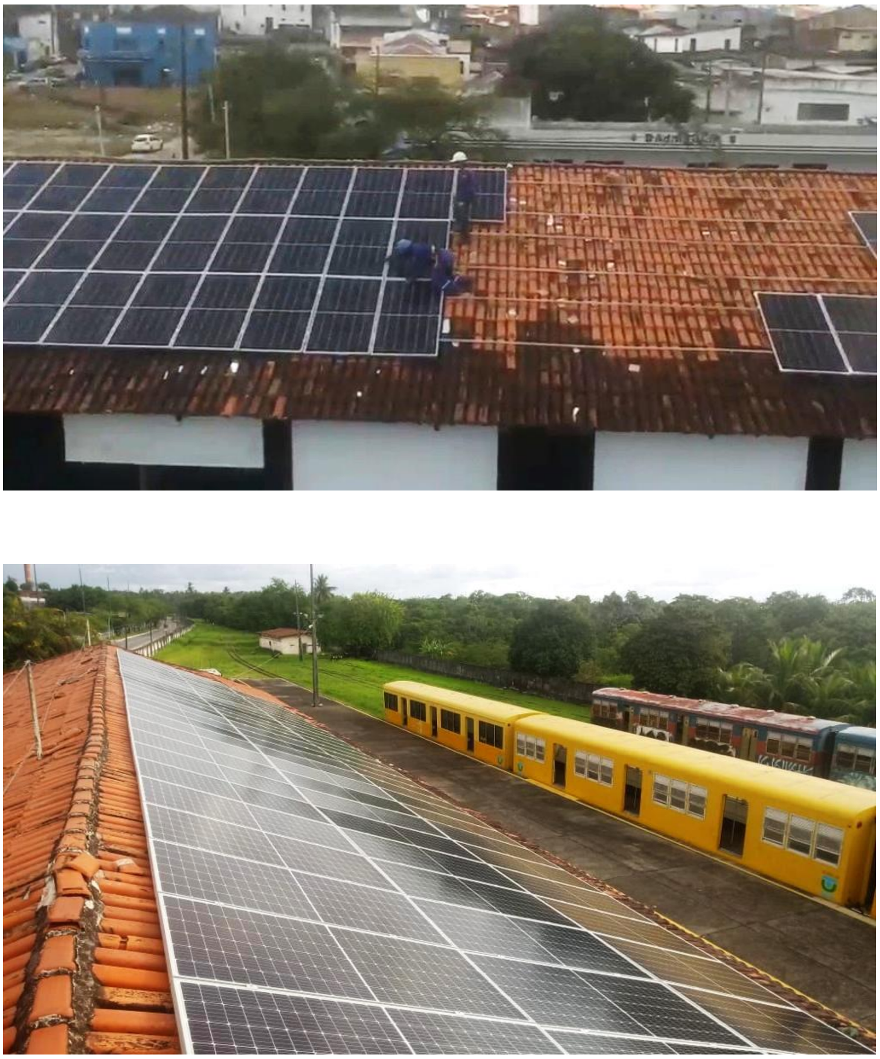

Fig. 2. Photovoltaic systems from Joao Pessoa office during (top) and after (down) installation.

Fig. 3 and Table 6 show the results of energy consumption of the period before and after PV system installation. The period of 2019 was compared to that from 2022 (until September), because 2020 and 2021 were atypical years affected by pandemic lockdowns. An average monthly reduction of 56% was observed in 2022. Other programs have achieved a 42.4% reduction on net-energy demand with a program to implement PV systems, a total replacement of actual lighting by LED and the implementation of a battery system using lithium-ion batteries with a capacity of 100 kWh (Fonseca et al., 2018).

Table 6. Energy consumption in the Paraiba rail system in 2019 and 2022.

Consumption (kWh)	**Year**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dez**
	2019	25.951	25.395	28.426	28.251	31.944	32.797	31.273	29.556	27.342	21.993	22.775	27.175
	2022	15.592	14.153	16.779	12.949	11.715	10.065	10.670	9.506	10.178	-	-	-
	Reduction	-40%	-44%	-41%	-54%	-63%	-69%	-66%	-68%	-63%			

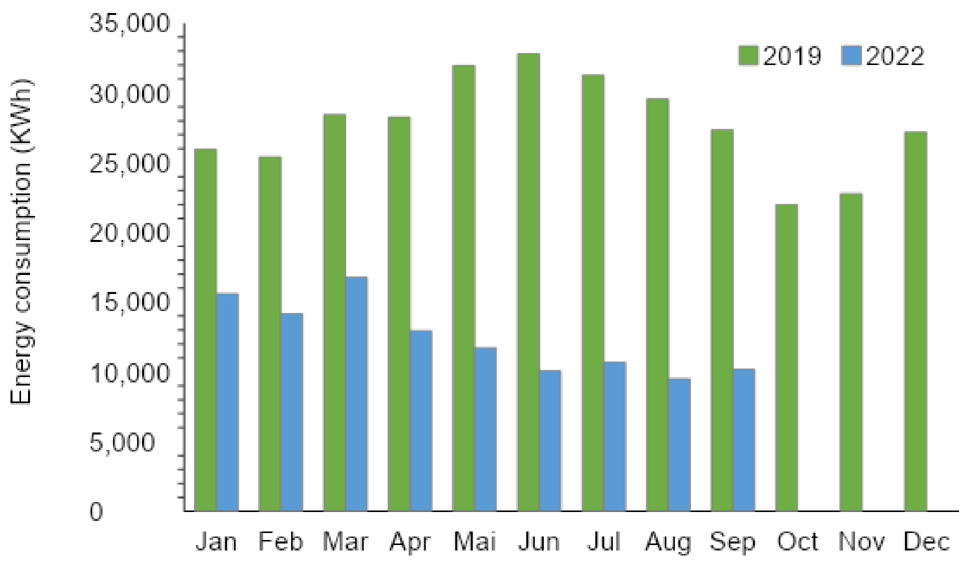

Fig. 3. Comparison of energy consumption in Paraiba rail company before (2019) and after (2022) photovoltaic system installation.

When comparing sustainable building research to the same energy-saving studies, most have achieved an average of 30 to 50% reduction in energy consumption by implementing sustainable projects with photovoltaic systems, replacement of inefficient lightning, and implementing new air conditioning and heating technologies (Meron and Meir, 2017, Katsaprakakis and Zidianakis, 2017, Khoshbakht et al., 2018).

3.3 Emission of Greenhouse Gas (GHG)

The photovoltaic system being originated from the solar energy, a renewable source, can also reduce the CO_2 emission. The reduction on CO_2 emissions related to the energy saving by the photovoltaic system was quantified. For the emissions of each GHG to be transformed into CO_2e emissions, the Global Warming Potential (GWP) was used. The GWP is an indicator of the ability of a gas to contribute to global warming and compares the heat factor in the atmosphere of a ton of a GHG for a given time interval with a ton of CO_2, showing the relative contribution of the emission to the atmosphere of 1t of a given GHG compared to the emission of 1t of CO_2 (INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, 2021, GOLDEMBERG, 2003). This time interval is called the time horizon, which represents the period of analysis counted from the instantaneous emission of the GHG (INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, 2021).

The analysis of carbon footprint has been done by adopting a streamlined lifecycle approach and the results are presented using a CO_2 e metric (MINISTÉRIO DA CIÊNCIA). This approach is in essence a slimmed down version of a complete LCA adopting all its core processes and excluding low contributing processes that would be otherwise included in a full LCA. The methodology adopted in this work for carbon footprint is based partially on the framework described by World Resources Institute (WRI) (WRI, 2011), The Ministry of Science, Technology, and Innovation of Brazil (MCTI) (MINISTÉRIO DA CIÊNCIA), and the conceptual LCA framework guidelines designated by the ISO (ISO, 2006a, ISO, 2006b).

In this context, to perform the calculation, the parameters of The Ministry of Science, Technology, and Innovation (MCTI) (MINISTÉRIO DA CIÊNCIA) were used, using the Eq. (1): GHG emission calculation for the purchase of electricity (WRI, 2011).

$$1.\quad \boldsymbol{ECO2, m, y} = \boldsymbol{Cm, y} \bullet \boldsymbol{FECO2, m, y}$$

Where ECO2 are the emissions attributable to electricity consumption from the national grid in month m of year y, in tCO_2e; Cm,y is the electricity consumption from the national grid in month m of year y, in MWh; FECO2 is the emission factor applicable to electricity from the national grid in month m of year y, in t CO_2/MWh; m is the month of consumption referring to electricity consumption; and y is the reference year.

The two-year epidemic prevented the rail system from operating at full capacity and prevented all staff from working. To better understand the true impact of The SWEC Program and the deployment of the solar system, it was decided to compare the years before and “after” the epidemic. Table 7 shows a comparison between the greenhouse gas emissions in 2019 and 2022.

The months with the lowest emissions of greenhouse gases were June, with 69%, August, with 67%, and July, with 65%, respectively. These months are winter in Brazil, but because to the region's proximity to the equator, the solar insulation remains constant, showing no seasonal variation reflected in the greenhouse gases emission stability in 2022.

More than 50% of GHG emissions were avoided in every month, indicating that the SWEC Program and the use of photovoltaic energy were successful to promote carbon reduction by the company.

Table 7. GHG Emission CO2 (t)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dez
2019	1.66	1.54	1.81	1.48	1.94	3.00	3.36	3.49	3.23	1.76	0.83	0.93
2022	1.00	0.86	1.07	0.68	0.71	0.92	1.15	1.12	1.20	-	-	-
GHG emission avoided	0.66	0.68	0.74	0.80	1.23	2.08	2.22	2.37	2.03	-	-	-

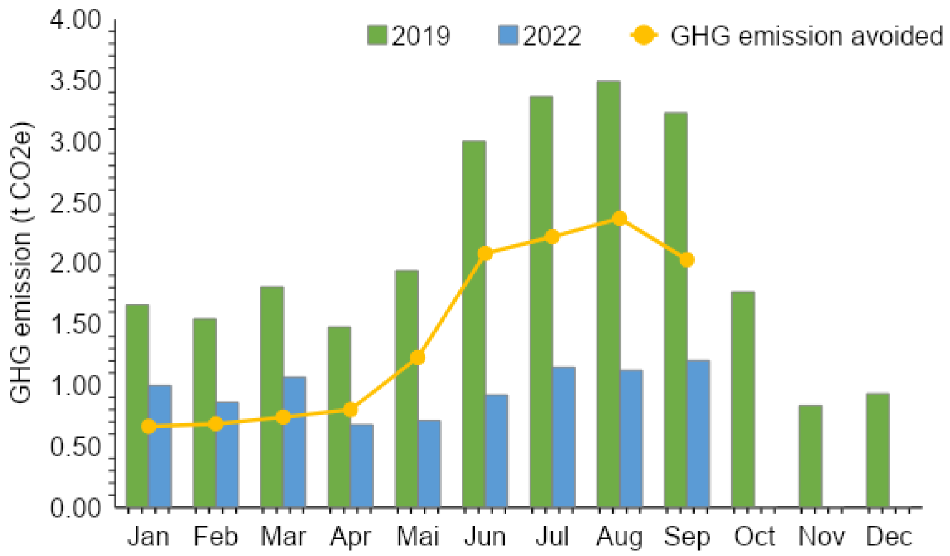

Figure 4. GHG emission in 2019 and 2022, after photovoltaic system installation.

4. Limitations and future work

The SWEC Program brought a radical shift in the rail company by changing the way employees thought about water and energy use, which helped to develop solutions and creative consumption habits. However, the Program´s execution was limited to the public budget and availability of personnel to carry out activities other than their regular responsibilities. The implementation of initiatives which depends on investments is very limited in the governmental companies, particularly in emerging economies.

Other technologies and devices are suggested to provide water and energy savings, such as motion sensor light switch, dual flush toilets, self-closing faucets, flow reducing devices and faucet aerators. The potential for savings with these items is significant, as it was estimated that each unit increase of each unit of water-saving devices resulted in a 0.512 decrease in water consumption level in households (Ali et al., 2020). Moreover, irrigation system and vegetation with lower water requirements can also be considered to reduce water consumption and consequently cost, after payback time (Andrade, 2019b).

The SWEC approach´s effectiveness is highly dependent on a continuous assessment of the consumption. It is wise to verify the consumption of each hydraulic and energy consuming items, as well as estimate the consumption of the railway passengers. A benchmarking study is also necessary to identify other best practices that were critical to water and energy savings at a mid-stage point.

Given that motivational variable impact water-saving behaviors and that basic actions may be suitable for integration into daily routine (Dean et al., 2021), the SWEC Program should revise its strategy to effectively motivate the employees on the issue while also aiming for long-term results.

5. Conclusions

The paper presented a methodology to implement a sustainable consumption approach of water and energy in the building. The methodology was validated in a public company, more specifically a railway company in Northeastern Brazil.

Permanent results were achieved by the SWEC Program implementation such as the acquisition of two photovoltaic systems with a total capacity of 96.5 kWp. The investment made provided a fast return with an average monthly reduction in energy consumption of 56% in 2022.

An overall evaluation for the SWEC Program revealed that the approach must be applied and evaluated on an ongoing basis. Water use was not reduced, and efforts such as analyzing each water-using device, quantifying consumption for passenger, and implementing the Program in other companies with comparable characteristics are necessary.

The SWEC Program has a strong appeal in sustainability and climate change actions. It decreased the emission of greenhouse gases by more than 50% on average per month, calculated by the reduction on energy use, leading to an average reduction of 1.4 ton of CO2 emission per month, and minimizing the environmental effect caused by the operation of the rail system.

The findings of this paper may be useful to other companies and industries, public or private, and other public institutions, such as universities and schools with large building and elevate consumption of water and electricity. Finally, this work contributed to the UN Agenda 2030, mainly to the Sustainable Development Goals 11 (Sustainable Cities and Communities), 7 (Affordable and Clean Energy), and 13 (Climate Action)

GENERAL CONCLUSIONS

This investigation conducted a retrospective bibliometric analysis of the railway sector, spanning a 20-year period from 2002 to 2021, with the aim of gaining a deeper understanding of railway research characteristics. The VOSviewer software was employed to create network maps from each of the studied variables. The findings displayed a substantial increase in the number of publications over this timeframe, notably highlighting the work of Zhang, Y.T., who emerged as the most prolific author. Engineering emerged as the most researched field of knowledge, with the Transportation Research Record being the journal with the highest publication count. China was revealed as the leading country in this research field, with Southwest Jiaotong University standing out as the principal institution.

Furthermore, a lack of research regarding the environmental impact and sustainability of railway systems was identified, presenting an area ripe for exploration in future studies.

Building on the bibliometric analysis that delineated railway research characteristics, the need for more investigation into sustainability and environmental impact in railway systems becomes evident. Within this context, this research underscores the growing global concern regarding climate change and its effects on climatic patterns. More specifically, the study zeroes in on the railway system of northeastern Brazil, aiming to assess greenhouse gas (GHG) emissions associated with this system and comparing them to relevant international case studies. The central objective of this research is to establish specific parameters for GHG emissions stemming from the railway system and, based on this understanding, devise mitigation strategies that effectively address this environmental impact.

To achieve this goal, the study adopts a comprehensive Life Cycle Assessment (LCA) methodology, allowing for a detailed analysis of the entire lifecycle of the railway system. This encompasses collecting real-world data to create a thorough inventory of GHG emissions. The study also provides a comparative analysis of GHG emissions across different urban railway transportation systems, offering valuable contextual perspectives.

The results presented in the abstract reveal that the total GHG emissions from the northeastern Brazilian railway system amount to 11,996.11 tCO_2e. With a projected lifespan of 50 years, estimates point to a total of 59,980,550 tCO_2e in GHG emissions over the operational and maintenance lifecycle of the system.

Presenting an enlightening view on GHG emissions mitigation, this research also observes the critical intersection between water scarcity, energy production, and global climate concerns. The mounting concern over water availability in various parts of the world is intricately linked to energy supply, particularly in countries like Brazil where electricity generation heavily relies on hydroelectric power plants. The mutual influence of water, energy, and CO_2 emissions, along with their climate effects, calls for a more holistic approach: the energy-carbon-water nexus.

Within this context, this research highlights the Sustainable Water and Energy Consumption (SWEC) Program, developed to address water and energy supply challenges in a Brazilian railway company. The program operated on several fronts, including user awareness, consumption analysis, establishing indicators for evaluating water and energy usage, and exploring cleaner alternatives for both sources. The impact was notable, with a reduction of 10% and 19% in per capita water and energy consumption, respectively. Furthermore, the program achieved lasting results, exemplified by the acquisition of photovoltaic systems with a total capacity of 96.5 kWp, leading to an average monthly energy consumption reduction of 56% in 2022. Additionally, over 50% of GHG emissions were eliminated each month, indicating the success of the SWEC Program and the use of photovoltaic energy in promoting carbon reduction by the company.

This work not only demonstrates an effective approach to tackling water and energy consumption challenges within a railway company but also aligns with global sustainability goals, such as the UN's Agenda 2030. The achieved results hold the potential to serve as a model for other companies, industries, and institutions, including universities and schools, seeking to enhance their consumption patterns.

One of the most notable emphases of this study is its interdisciplinary approach, highlighting the importance of examining the atmospheric effects of the railway system. This approach aims to develop strategies and technologies that can mitigate air pollution. The quantification and analysis of GHG emissions play a pivotal role, not only in addressing climate change concerns but also in promoting sustainable practices.

In the current landscape, where sustainability and climate change mitigation take center stage, this study significantly contributes to Sustainable Development Goals (SDGs) and the development of a clearer understanding of GHG emissions associated with the railway system. Furthermore, by emphasizing the importance of Life Cycle Assessment and an interdisciplinary approach, this study not only provides valuable insights for public policies and decision-making but also guides efforts toward a more sustainable railway transportation system.

FUTURE LINES OF RESEARCH

Research in the field of greenhouse gas (GHG) inventory has the potential to bring significant advancements to the understanding and mitigation of climate change. In concluding this research, there are gaps that could be addressed in future studies. Some promising areas of focus include:

Development of Advanced Models: Research can concentrate on enhancing GHG inventory models by incorporating more accurate data and real-time information. Advanced models will allow for a more detailed estimation of emissions, considering factors such as seasonal variations, climatic conditions, and energy use.

Enhancement of Monitoring: Remote sensing technologies and real-time measurement devices can be employed to directly monitor emissions from various sources, such as urban railway systems.

Consideration of Indirect and Dynamic Flows: In addition to direct emissions, it is important to assess indirect flows and complex interactions between different sectors of the economy. This will provide a more holistic understanding of emissions and their climate impact.

Integration of Socioeconomic Data: Understanding how socioeconomic factors influence emissions is crucial for effective policy formulation. Research can explore how changes in consumption patterns, urbanization, and economic development affect emissions.

International Comparison: Comparing GHG inventories of railway systems across different countries can identify best practices and areas for improvement. This can contribute to method harmonization and global collaboration in climate change mitigation.

Technological Innovations: Research should keep pace with the development of innovative technologies, such as renewable energy sources for train traction, carbon storage, and carbon capture, which may alter the global railway emissions landscape in the future.

Circular Economy: The circular economy concept aims to minimize waste and optimize resource usage, promoting reuse, recycling, and regeneration of materials and products. Incorporating circular economy studies within the methodology of the life cycle will enhance the environmental and economic sustainability of the railway system.

Water Footprint Analysis: Future studies of water footprint analysis within the railway system will evaluate water use throughout the entire life cycle of railway operations, from construction to operation and maintenance. These studies will help in understanding the quantification of both directly and indirectly associated water use in the railway system, considering both consumed and polluted water.

Overall, future research on the life cycle analysis of the railway system is essential to provide a solid foundation of data and knowledge that guides decision-making in public policies and actions to effectively and sustainably combat climate change.

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