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**DESFECHOS EM SAÚDE RELACIONADOS À POLUIÇÃO DO AR EM UM
MUNICÍPIO DA REGIÃO CENTRO-OESTE DO BRASIL**

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**DESFECHOS EM SAÚDE RELACIONADOS À POLUIÇÃO DO AR EM UM
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RESUMO

A qualidade do ar é um parâmetro fundamental para a garantia do bem-estar e da manutenção da saúde de uma população. A exposição a diferentes poluentes configura importante causa de adoecimento, levando ao aumento da taxa de mortalidade por doenças cardiorrespiratórias e consequentemente, redução da expectativa de vida e gastos na recuperação da saúde. A região Centro-Oeste do Brasil, na qual se encontra o Estado de Mato Grosso, é a que mais se destaca na agricultura e na pecuária. Graças a esse tipo de produção, há grande consumo de agrotóxicos e importantes mudanças geográficas pela substituição de áreas de vegetação por pastagens, favorecendo o surgimento de focos de calor e incêndios, evolução do processo de desertificação, alterações climáticas e acúmulo de xenobióticos no ambiente. Sendo assim é fundamental dimensionar os impactos que vêm passando despercebidos à população, devido ao deficiente processo de monitoramento destes contaminantes, em especial suas concentrações na atmosfera. Para tal, serão coletadas informações referentes aos poluentes do ar, dados meteorológicos e de incêndios florestais em um município de médio-porte situado na região Centro-Oeste, a partir de dados de modelagem de satélite, bem como indicadores populacionais e de saúde destas populações a fim de: primeiramente avaliar o padrão e dinâmica dos principais poluentes do ar, sua relação com parâmetros meteorológicos, sazonalidade e episódios críticos e além disso, avaliar o impacto dos poluentes do ar sobre indicadores de saúde na população, com foco nas mortes evitáveis relacionadas. E, isto posto, com os resultados a serem obtidos pelo presente estudo, avançar na proposição de alternativas de enfrentamento e mitigação de impactos, que favoreçam o alcance das metas da Organização Mundial da Saúde quanto à saúde/segurança ambiental.

Palavras-chave: Ecotoxicologia. Incêndios. Material particulado. Poluição do ar. Risco. Saúde humana.

Objetivos de Desenvolvimento Sustentável contemplados na proposta:

ODS 3 Saúde e Bem-estar: Garantir o acesso à saúde de qualidade e promover o bem-estar para todos, em todas as idades.

ODS 11 Cidades e comunidades sustentáveis: Tornar as cidades e os assentamentos humanos inclusivos, seguros, resilientes e sustentáveis.

ODS 13 Ação contra a mudança global do clima: Tomar medidas urgentes para combater a mudança climática e seus impactos.

ABSTRACT

Air quality is a fundamental parameter for the well-being and health of a population. Exposure to various pollutants is an important cause of disease, leading to an increase in the mortality rate from cardiorespiratory diseases and, consequently, to a reduction in life expectancy and expenditure on health recovery. The Central-Western region of Brazil, where the state of Mato Grosso is located, is the one that stands out the most in agriculture and livestock production. This type of production leads to high consumption of pesticides and significant geographical changes, as vegetation areas are replaced by pastures, which favors the creation of hotspots and fires, the development of desertification, climate change, and the accumulation of xenobiotics in the environment. It is therefore important to measure the effects that have gone unnoticed by the population due to the inadequate monitoring of these pollutants, particularly their atmospheric concentrations. To this end, information on air pollutants, meteorological and forest fire data based on satellite modeling data, and population and health indicators will be collected in a medium-sized municipality in the Central-West region to first, assess the pattern and dynamics of key air pollutants, their relationship to meteorological parameters, seasonality, and critical episodes; and besides that, assess the impact of air pollutants on population health indicators, with a focus on associated preventable deaths. With the results of this study, we expect to propose alternatives to manage and mitigate the impacts, helping to promote the achievement of the World Health Organization's health and environmental safety goals.

Keywords: Ecotoxicology. Wildfires. Particulate matter. Air pollution. Risk. Human health.

Sustainable Development Goals included in the proposal:

SDG 3 Good health and Well-being: Ensure access to quality healthcare and promote well-being for all, at all ages.

SDG 11 Sustainable cities and communities: Make cities and human settlements inclusive, safe, resilient, and sustainable.

SDG 13 Climate action: Take urgent action to combat climate change and its impacts.

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LISTA DE ABREVIATURAS

Entidades elementares:

As	- Arsênio
Cd	- Cádmio
CFCs	- Clorofluorcarbonos
CH ₄	- Metano
CO	- Monóxido de carbono
CO ₂	- Dióxido de carbono
COVs	- Compostos orgânicos voláteis
FMC	- Fumaça
HCl	- Ácido clorídrico
HF	- Ácido fluorídrico
NH ₃	- Amônia
NO	- Óxido nítrico
NO ₂	- Dióxido de nitrogênio
NO _x	- Óxidos de nitrogênio
O ₃	- Ozônio
PAN	- Peroxiacetilnitrato
Pb	- Chumbo
PM ₁₀	- Material Particulado grosso, partículas menores que 10 µm;
PM _{2,5}	- Material Particulado fino, partículas menores que 2,5 µm;
PCVCs	- Poluentes climáticos de vida curta
PTS	- Partículas totais em suspensão
SO ₂	- Dióxido de enxofre
SO ₃	- Trióxido de enxofre

Demais abreviaturas e siglas:

BE	- Espaço urbano
CEMADEN	- Centro Nacional de Monitoramento e Alertas de Desastres Naturais
CMAQ	- Sistema de modelagem da qualidade do ar comunitária multiescala
CONAMA	- Conselho Nacional do Meio Ambiente

DATASUS	- Departamento de informática do Sistema Único de Saúde (SUS)
ECMWF	- Centro Europeu de Previsões Meteorológicas de Médio Prazo
EMBRAPA	- Empresa Brasileira de Pesquisa Agropecuária
EPA/USEPA	- Agência de proteção ambiental Norte-Americana
HIA/AIS	- Avaliação de Impacto à Saúde
IBAMA	- Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais
Renováveis	
IBGE	- Instituto Brasileiro de Geografia e Estatística
IBRAM	- Instituto do Meio Ambiente e dos Recursos Hídricos do Distrito Federal
ICMBio	- Instituto Chico Mendes de Conservação da Biodiversidade
IEMA	- Instituto de Energia e Meio Ambiente
INMET	- Instituto Nacional de Meteorologia
IPCC	- Painel Intergovernamental sobre Mudanças Climáticas
MS	- Ministério da Saúde
MT	- Mato Grosso
NAQS	- National Air Quality Standards, Padrões nacionais de qualidade do ar
ODS	- Objetivos de Desenvolvimento Sustentável
OMS	- Organização Mundial da Saúde
ONU	- Organização das Nações Unidas
PRONAR	- Programa Nacional de Controle da Qualidade do Ar
SVS	- Secretaria de Vigilância em Saúde
UNEP	- United Nations Environment Programme
VIGIAR	- Programa de Vigilância em Saúde de Populações Expostas à Poluição
Atmosférica	

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1. INTRODUÇÃO

A contaminação ambiental é um processo profundamente enraizado na influência humana, proveniente de diversas atividades associadas à produção, consumo e descarte de bens e matérias-primas (Russo *et al.*, 2021). Neste contexto, emerge uma crescente preocupação com as diferentes substâncias e produtos que entram em contato com a atmosfera, o solo e a água, reagindo entre si de maneira imprevisível e colocando em risco o equilíbrio dos ecossistemas e a saúde humana (Styszko *et al.*, 2021).

Dentro da ecotoxicologia, a poluição atmosférica é uma das grandes frentes de estudo e encontra, em anos recentes, papel de protagonismo por ser ubíqua (Da Silva Júnior *et al.*, 2023) e por suas implicações diretas com mudanças climáticas (D'Amato e Akdis, 2020), desastres ambientais (Burhan e Mukminin, 2020) e até mesmo distribuição espacial de vetores de diversas patologias (Leal Filho *et al.*, 2018).

Evidências indicam que a poluição atmosférica é conhecida desde a antiguidade (Fowler *et al.*, 2020), porém, sua conceituação moderna remonta à Revolução Industrial, quando a liberação de poluentes atmosféricos foi acelerada e passou a ser em grande escala (Fowler *et al.*, 2020). Desde então, a intensificação das atividades humanas, a urbanização acelerada e o aumento da frota de veículos automotores contribuíram para um aumento constante na concentração de poluentes atmosféricos.

A Revolução Industrial marcou o início de uma era em que a produção em massa e a queima de combustíveis fósseis se tornaram a espinha dorsal da economia mundial. À medida que a produção e o consumo aumentavam, os níveis de poluição do ar também cresciam exponencialmente. Durante grande parte do século XX, a poluição do ar era frequentemente vista como um subproduto inevitável do progresso industrial (Power *et al.*, 2018).

Os impactos da poluição atmosférica vão muito além de meros danos estéticos. Ela afeta diretamente a saúde humana, prejudicando o sistema respiratório e contribuindo para uma série de problemas de saúde, desde doenças respiratórias crônicas até doenças cardíacas. Além disso, a exposição prolongada à poluição do ar está associada a um aumento de nascimentos prematuros e crianças com baixo peso ao nascer, como revelam estudos epidemiológicos (Bekkar *et al.*, 2020; Soares *et al.*, 2022). Estudos como o de Orru, Ebi e Forsberg (2020) apontam estar ligada a mais de sete milhões de mortes anuais mundialmente.

Essas consequências, porém, não se limitam apenas à saúde humana. Ecologicamente, a poluição atmosférica pode causar danos significativos aos ecossistemas naturais. A deposição ácida, um fenômeno relacionado à emissão de dióxido de enxofre (SO₂) e óxidos de nitrogênio (NO_x), pode acidificar solos e corpos d'água, prejudicando a flora e a fauna (Stevens *et al.*, 2020). Além disso, a presença de poluentes atmosféricos afeta a qualidade do ar, tornando-o inadequado para organismos aeróbios e levando à degradação da biodiversidade local (Singh, Shukla e Singh, 2020).

Diante desse cenário, a região Centro-Oeste do Brasil desempenha um papel de destaque no contexto ambiental e agrícola do país. Abrangendo parte dos biomas Amazônico, Cerrado, Pantanal e Mata Atlântica, essa região é um microcosmo da diversidade ecológica do Brasil (Bacarji, Vilpoux e Paranhos Filho, 2021). As complexidades ecológica e social dessa região estão diretamente ligadas às atividades antropogênicas que as moldaram no passado e ainda as influenciam intensamente, especialmente quando se considera que para a América do Sul, como um todo, o século XX foi o de atmosfera mais poluída (Uglietti *et al.*, 2015) e essa condição permanece nas primeiras décadas do século XXI.

Em Mato Grosso (MT), a expansão agrícola tem sido notável, com vastas áreas convertidas em plantações de soja, milho e algodão, além de pastagens para o gado. Essa expansão trouxe prosperidade econômica tornando o estado uma das maiores fronteiras agrícolas do mundo (Simões *et al.*, 2020), mas também desafios ambientais significativos. O desmatamento associado ao avanço da agricultura vem afetando diretamente a riqueza e abundância de espécies e o ciclo hidrológico da região (Da Silva, Lopes e Santos, 2023).

Nesse contexto, a relação entre a expansão agrícola, a poluição atmosférica e seus efeitos na saúde humana se torna evidente. O uso extensivo de pesticidas nas plantações e os incêndios florestais frequentes, muitas vezes associados ao desmatamento, contribuem para a emissão de poluentes atmosféricos prejudiciais (Lopes-Ferreira *et al.*, 2023; Oliveira *et al.*, 2023). Isso coloca em risco não apenas o ambiente, mas também a saúde das populações urbanas próximas, que estão expostas a uma qualidade do ar comprometida (Alves, 2020; Caumo *et al.*, 2022).

Além das implicações para a saúde e o meio ambiente, a poluição atmosférica também tem um custo econômico significativo. A poluição do ar leva a uma série de gastos, incluindo despesas médicas relacionadas ao tratamento de doenças causadas pela poluição, perda de produtividade entre os trabalhadores e também no rendimento de culturas agrícolas (Santana *et al.*, 2020; De Moura e Da Silva Júnior, 2023). Estudos

econômicos têm destacado os custos substanciais associados à poluição do ar, sublinhando a necessidade de medidas de mitigação eficazes (Sofia *et al.*, 2020). E, não se pode negligenciar a relação da poluição atmosférica com as mudanças climáticas. Os poluentes atmosféricos, como o dióxido de carbono (CO₂), metano (CH₄) e óxidos de nitrogênio (NO_x), contribuem para o aumento do efeito estufa e, consequentemente, para o aquecimento global. Esse fenômeno está associado a eventos climáticos extremos, como secas, ondas de calor, enchentes e tempestades mais intensas (Zandalinas, Fritschi e Mittler, 2021).

Considerando que o Centro-Oeste do Brasil desempenha um papel crítico na produção agrícola e pecuária do país, é imperativo entender como as atividades humanas afetam a qualidade do ar, o clima regional e a saúde das populações. Dessa forma, este estudo tem como objetivo quantificar os níveis de poluição do ar, avaliar seus impactos climáticos e examinar seus efeitos na saúde em Sinop, um município da região norte do Mato Grosso, estrategicamente localizado no ecótono Cerrado-Amazônia.

Ao quantificar os níveis de poluição e seus efeitos, esperamos fornecer subsídios científicos que estimulem a elaboração de políticas públicas para mitigação da poluição do ar e a promoção da saúde pública. Não obstante, esperamos que esta pesquisa contribua para a conscientização pública sobre os desafios ambientais e de saúde na região Centro-Oeste e inspire ações individuais e coletivas em prol da sustentabilidade.

Este estudo se alinha diretamente com os Objetivos de Desenvolvimento Sustentável (ODS) da Organização das Nações Unidas (ONU). Em particular, aborda os ODS 3, 11 e 13. O entendimento dos efeitos da poluição atmosférica nessas áreas críticas é essencial para avançar em direção a um futuro mais sustentável.

2. REFERENCIAL TEÓRICO

2.1 Poluentes atmosféricos

O ar poluído consiste numa mistura de partículas e gases que assumem no ambiente efeitos nocivos e que são oriundos de diversos processos (emissões) naturais – tais como queima de biomassa (descargas elétricas), spray marinho e erupções vulcânicas – ou emissões artificiais (antropogênicas), que incluem atividade industrial, incêndios, queima de combustíveis fósseis, veículos automotivos e usinas termelétricas e hidrelétricas (Santos *et al.*, 2019). No caso das hidrelétricas, durante algum tempo,

acreditava-se que eram fontes limpas de energia, porém, com o passar do tempo percebeu-se que principalmente nos primeiros anos após a formação dos lagos, a decomposição da vegetação submersa dá origem a gases como o metano, o gás carbônico e o óxido nitroso, todos eles relacionados às mudanças climáticas (Lu *et al.*, 2020). De acordo com dados do Seminário de Preparação do Setor Saúde para a Estação de Queimadas 2022, a poluição atmosférica representa, hoje, a maior preocupação nos estudos de contaminação ambiental, superando largamente as poluições aquática e do solo, tanto em termos de alcance espacial como de tempo de duração dos impactos causados, que podem ser inclusive, definitivos.

Há muitos compostos que são classificados como poluentes atmosféricos, podendo ser divididos em compostos de enxofre (SO_2 , SO_3 , mercaptanas), compostos de nitrogênio (NO , NO_2 , NH_3), compostos orgânicos (hidrocarbonetos álcoois, cetonas, aldeídos), compostos simples de carbono e associações (CO , CO_2 , carbono negro), compostos halogenados (HF , HCl), metais e metaloides (Pb , Cd , As), material particulado e oxidantes fotoquímicos (O_3 , formaldeído, PAN - peroxiacetilnitrato, acroleína).

Essas substâncias podem ter origem primária (diretamente da fonte emissora, como SO_2 e NO_2) ou secundária (por reações químicas ocorridas na atmosfera com compostos naturais do ambiente, como O_3 e o ácido sulfúrico - H_2SO_4). Conforme mencionado por Raposo Junior, Norton e Assis (2021), dentre os poluentes de maior destaque podem-se elencar: o material particulado ($\text{PM}_{2,5}$ e PM_{10}), os óxidos de nitrogênio (NO_2 e NO_x), compostos orgânicos voláteis (COVs), dióxido de enxofre (SO_2), monóxido de carbono (CO) e ozônio (O_3).

Considerando esses compostos, CO é um subproduto da queima incompleta de combustíveis fósseis, originando-se principalmente a partir de veículos, indústrias, lareiras, fornos domésticos e outros incineradores lentos. Apesar de poder desempenhar papel de importância na regulação de mecanismos fisiológicos e ser um candidato recente à produção de fármacos, essa substância induz à asfixia química por sua ligação irreversível à hemoglobina, reduzindo a quantidade de oxigênio que pode ser transportado para órgãos essenciais (Adach, Blaszczyk e Olas, 2020).

Já o SO_2 atmosférico, por sua vez, pode ser de origem natural, a partir de erupções vulcânicas, mas também pode ser produzido pela atividade humana através da queima do carvão e do petróleo. Na atmosfera esse composto é precursor dos sulfatos que ajudam a compor o material particulado (PM_{10}) e se combina com vapores d'água dando origem ao

H₂SO₄, substância que além de participar do processo de formação da chuva ácida, está implicada em patologias respiratórias e cardiovasculares (Craig, 2019).

Os compostos de nitrogênio (NO₂ e NO_x) são gases altamente reativos e costumam derivar de grande tráfego veicular, usinas termoelétricas e equipamentos *off-road*, mas estão presentes na fumaça de cigarros e participam da formação de outros poluentes como o ozônio troposférico e o material particulado. No organismo causam toxicidade ao sistema respiratório agravando doenças pré-existentes e aumentando o risco de desenvolver asma. Além disso, são potencialmente mutagênicos e capazes de afetar o sistema nervoso e reprodutor (Correa, Aranda e Riquelme, 2021).

Os COVs são gases e vapores que, além de outras fontes, podem surgir da queima incompleta de madeira e carvão em domicílios, e incluem compostos como o benzeno, o tolueno, e os xilanos, que se vaporizam com facilidade e em presença de luz solar, sofrem reações fotoquímicas que podem levar à formação do ozônio e do fenômeno de *smog*, correlacionado a queda drástica de qualidade do ar e agravamento de problemas cardiovasculares (Javed *et al.*, 2021).

O ozônio troposférico é um composto de origem secundária, formando-se no ambiente a partir das reações fotoquímicas de NO_x e COVs, e, enquanto poluente, é altamente reativo, de difícil controle e está associado aos fenômenos de estresse oxidativo, envelhecimento precoce e agravamento de inúmeras condições patológicas como doenças respiratórias em crianças (Silva *et al.*, 2016). Nos ambientes urbanos, em especial nas regiões com elevado índice de radiações ultravioleta, o O₃ é um dos poluentes mais preocupantes em relação à manutenção dos padrões de qualidade do ar (EPA, 2023).

Já o material particulado, um grupo de poluentes de elevada importância clínica, é formado por uma mistura de matéria em estado líquido e sólido, em suspensão, tais como poeira, fumaça, fuligem, pólen e partículas do solo, e geralmente é classificado em: partículas totais em suspensão (PTS), fumaça (FMC), PM₁₀ (partículas com diâmetro ≤ 10µm), chamado de material particulado grosso e o PM_{2,5} (partículas com diâmetro ≤ 2,5µm) que é o material particulado fino (Torres *et al.*, 2020).

Ainda se classifica o material particulado em ultrafino (PM_{0,1} ou partículas com diâmetro ≤ 0,1µm), que, no entanto, é menos frequente em estudos. Todas essas partículas compõem a fração inalável por serem menores que o diâmetro de um fio de cabelo humano (60 µm), sendo que, quanto menor o diâmetro da partícula, mais profundamente ela é capaz de penetrar no trato respiratório, provocando danos potencialmente maiores

ao organismo, já havendo estudos que apontam sua relação com cânceres ou a doença de Alzheimer após alcançar a circulação sistêmica (Benabed e Boulbair, 2022).

Finalmente, embora menos estudos se dediquem à avaliação de metais e metaloides na atmosfera, quando se compara com o material particulado, por exemplo, inclusive devido às limitações para sua adequada quantificação, elementos como chumbo (Pb), cádmio (Cd), vanádio (V) e arsênio (As) despertam a atenção de vários grupos de pesquisa. Espécies vegetais vêm sendo utilizadas para quantificação desses elementos no ambiente, chegando a surpreendentes resultados de níveis muito acima do esperado (Beringui *et al.*, 2021). É oportuno mencionar que o advento de políticas públicas, como a que eliminou o uso de Pb como aditivo da gasolina definitivamente, no Brasil, a partir de 1992, trouxeram importante diminuição dos níveis desse elemento na atmosfera, embora estudos ainda apontem para sua presença significativa (Gioia *et al.*, 2017).

2.2 Fontes poluidoras

As fontes poluidoras ou emissoras de poluentes atmosféricos também devem ser categorizadas, com a finalidade básica de se desenvolverem inventários de emissões (Xu *et al.*, 2020). Definem-se como fontes fixas, pontuais ou estacionárias aquelas que, como o nome define, estão estabelecidas num ponto único, tais como refinarias, indústrias químicas, metalúrgicas, minas, etc. Nesses locais os poluentes são geralmente emitidos para a atmosfera através de chaminés, *vents* (dutos de ventilação) ou *flares* (tochas para queima de correntes gasosas em condições emergenciais) (Bhattacharyya, 2019).

Há também as fontes móveis, ou seja, que não estão fixas em um único local, e que identificam, em geral, os meios de transporte. Nesse sentido podem ser classificadas como: rodoviárias – caminhões, carros, motocicletas e demais veículos que circulam em rodovias, e não rodoviárias – representadas por meios de transporte que não trafegam em rodovias como aviões, barcos, trens, etc (Tiwary e Williams, 2018). Incêndios florestais também são classificados como fontes emissoras e representam a mais grave problemática nas regiões do Brasil central e da Amazônia (De Simoni *et al.*, 2021; UNEP, 2022).

Além destas, outras classificações podem ser propostas como as fontes de emissões fugitivas, resultantes de vazamentos em tubulações ou equipamentos; fontes volumes (tridimensionais) e fontes áreas, que incluem várias pequenas fontes emissoras, que geralmente só representam uma problemática quando consideradas em conjunto,

como áreas de agricultura, criação de animais, depósitos de lixo e queima doméstica (Tiwary e Williams, 2018). A figura 1 apresenta um infográfico das principais fontes poluidoras.

Figura 1 – Fontes de poluição atmosférica.



Fonte: OMS, 2021 (<https://www.who.int/data/gho/data/themes/air-pollution>)

2.3 Impactos da poluição atmosférica

A necessidade do controle das emissões de poluentes na atmosfera está diretamente relacionada aos impactos desses compostos sobre a saúde humana, o meio ambiente e à economia. A Organização Mundial da Saúde (OMS) estima que 99% da população mundial esteja exposta à poluição do ar (UNEP, 2019; OMS, 2022), mas alguns subgrupos demonstram ser mais sensíveis: crianças muito pequenas, cujos sistemas circulatório e respiratório não estão plenamente desenvolvidos; idosos, que já apresentam limitações no funcionamento desses sistemas, pessoas portadoras de doenças

crônicas e certos trabalhadores devido à natureza de sua ocupação (Barthelemy *et al.*, 2020). Esse quadro pode ser facilmente agravado se somado à presença de vulnerabilidade econômica nesses grupos.

Várias patologias podem ser atribuídas à exposição aos diversos tipos de poluentes atmosféricos, sendo que o tempo de exposição e a natureza do poluente influenciam diretamente nessas respostas, que podem variar do nível subclínico até a letalidade. Nesse sentido, conforme apontado por De Simoni *et al.* (2021), pesquisas realizadas por inúmeros grupos já apontaram para efeitos nocivos como doenças pulmonares, cardiovasculares e hematológicas, vários quadros alérgicos e dermatológicos, infertilidade, doenças reumáticas, aumento da predisposição à cânceres, diabetes, demência e prejuízo cognitivo e inclusive danos prévios ao nascimento (baixo peso ao nascer, prematuridade).

Esses desafios não ficam restritos ao campo da saúde, mas se estendem ao âmbito econômico. Além dos custos inerentes aos cuidados com saúde e mortalidade prematura, a morbidade decorrente da poluição atmosférica também gera impactos econômicos significativos em outras áreas. Isso inclui despesas ligadas ao mercado de trabalho, como ausências prolongadas devido a doenças relacionadas à poluição e redução da produtividade de trabalhadores afetados (Lu, 2019). Similarmente, a poluição do ar pode causar perda de produtividade agrícola devido aos efeitos adversos sobre as plantações, à biodiversidade dos animais polinizadores e à microbiota e estrutura do solo (Luo *et al.*, 2019; Plutino *et al.*, 2022).

Efeitos indiretos sobre a aquisição de habilidades educacionais também podem ser verificados. Crianças expostas a níveis elevados de poluição do ar podem enfrentar dificuldades de aprendizado devido a problemas de saúde, como asma, que resultam em faltas frequentes (Holm, Miller e Balmes, 2021). Tal fenômeno tem importantes custos econômicos a longo prazo, uma vez que afeta o desenvolvimento educacional e, conseqüentemente, as oportunidades de emprego e a produtividade futura da força de trabalho de uma região ou país.

2.4 Mudanças climáticas

Há uma ligação importante entre a poluição atmosféricas e as mudanças climáticas, conforme mencionado por Fernandes, Hacon e Novais (2021). Isso ocorre em duas frentes: primeiro, alguns poluentes, conhecidos como poluentes climáticos de vida

curta (PCVC), contribuem tanto para a poluição do ar quanto para as mudanças climáticas (Xiaopu *et al.*, 2022); em segundo lugar, diversas fontes emissoras produzem tanto os poluentes climáticos como os convencionais. Essa percepção pode ser favorável para a implementação de políticas que regulem tanto os padrões de qualidade do ar, como também possam trazer benefícios para retardar as mudanças climáticas.

Os PCVC são gases e partículas com uma vida relativamente curta na atmosfera, variando de alguns dias a uma década. Isso os diferencia dos gases de efeito estufa tradicionais, como o dióxido de carbono, que podem permanecer na atmosfera por séculos. Os principais PCVCs incluem o carbono negro, o metano, alguns precursores do O₃ troposférico (como monóxido de carbono e compostos orgânicos voláteis) e hidrocarbonetos, que são contribuintes significativos para as mudanças climáticas após o CO₂. O carbono negro, em particular, desempenha um papel importante na absorção de radiação solar de onda curta (Gioda, Tonietto e Leon, 2019).

Artaxo (2020) ressalta que para os países em desenvolvimento, pensar em alternativas para redução das mudanças climáticas é algo ainda mais desafiador do ponto de vista social e tecnológico do que nas nações desenvolvidas. Isso porque, esses países possuem vulnerabilidades específicas, como maior risco de insegurança alimentar, menor resiliência perante eventos extremos (secas, inundações, incêndios florestais), serviços de saúde menos estruturados ou com menor disponibilidade de recursos e menor infraestrutura científico-tecnológica para o advento de alternativas de mitigação (Eriksen *et al.*, 2021)

Considerando que o aquecimento global é um fenômeno em aceleração e que é capaz de alterar desde o regime de chuvas até a distribuição territorial dos seres vivos, compreender melhor sua dinâmica e analisar cenários futuros são ações fundamentais para orientar políticas públicas baseadas em evidências científicas.

2.5 Fatores que podem influenciar a qualidade do ar

A qualidade do ar é dependente de diversos fatores. A topografia, a ocupação e uso do solo e as variáveis meteorológicas podem ou não favorecer a dispersão de compostos na atmosfera e, em se tratando de poluentes, isso impacta diretamente a qualidade do ar, tanto do ponto de vista momentâneo quanto permanente.

Em se tratando do relevo, a presença de áreas montanhosas pode, por exemplo, favorecer a ocorrência de fenômenos como a inversão térmica, na qual uma camada de

frio fica aprisionada próxima à superfície, impossibilitando a circulação dos ventos e causando o acúmulo de poluentes por períodos mais prolongados, com grandes consequências à saúde da população residente na região (Feng, Wei e Wang, 2020). A poeira, a fumaça emitida nos incêndios e gases oriundos de fontes naturais como vulcões em atividade também podem comprometer de forma drástica e repentina a qualidade do ar (Bauer *et al.*, 2019; Requia *et al.*, 2021; Filonchyk *et al.*, 2022).

Ainda, o processo de urbanização é outro fator importante para este cenário por interagir diretamente com os aspectos meteorológicos. Como as disposições e a altura das edificações são capazes de alterar a velocidade e a direção das correntes de vento, a transferência térmica pode ficar prejudicada, intensificando fenômenos como as ilhas de calor e a concentração de poluentes (Maia, Netto e Costa, 2019). Além disso, compostos presentes na baixa atmosfera podem sofrer deposição úmida/seca e consequentemente interagirem com outras substâncias acarretando alterações na paisagem urbana ou nos ecossistemas.

Variáveis meteorológicas também devem ser consideradas no estudo da dinâmica dos poluentes atmosféricos, isso porque, num cenário em que as emissões sejam mantidas, a qualidade do ar será diretamente dependente de quanto as condições meteorológicas serão ou não capazes de dispersar os poluentes (Liu *et al.*, 2023). Meses de inverno costumam ser mais propícios para o acúmulo de poluentes como SO₂, material particulado e CO, enquanto o O₃, devido à sua dependência para com a radiação solar, costuma preponderar em meses mais quentes como os do verão (CETESB, 2020).

Dentre as condições meteorológicas comumente contempladas em estudos da poluição atmosférica devido aos seus efeitos sobre a dispersão dos poluentes, podem ser incluídas: a pressão atmosférica e sua estabilidade, a temperatura ambiente e a amplitude térmica, o nível de radiação UV solar, a umidade relativa do ar, a precipitação pluviométrica e a direção e velocidade dos ventos. Geralmente na escala local, o vento e o nível de estabilidade atmosférica são os fatores de maior preponderância nessa relação (CETESB, 2020).

Estudos realizados em diferentes locais do território brasileiro reforçam essas correlações, como Silva Júnior e colaboradores (2020) que analisaram dados de nove municípios do extremo sul do Brasil e observaram correlação positiva ou negativa de todos os poluentes analisados (O₃, NO₂, SO₂, PM_{2,5}, PM₁₀ e CO) com pelo menos uma variável meteorológica. Silveira *et al.* (2023), também observaram que a formação de ondas de calor na região Amazônica está associada com aumento do risco de óbito por

causas não externas e doenças cardiovasculares, sendo que a intensidade dessas ondas, demonstrou ter mais influência sobre esses desfechos que sua duração.

Esses e outros achados disponíveis na literatura específica evidenciam a necessidade do monitoramento da qualidade do ar, a fim de se ter conhecimento do tipo e da quantidade de emissões que são realizadas por diferentes atividades antropogênicas.

2.6 Marcos regulatórios e monitoramento da qualidade do ar

O estudo da poluição atmosférica não despertava grande interesse na comunidade científica há cerca de um século. Muito embora preocupação e insatisfação com episódios notórios de poluição atmosférica existam há muito nos registros históricos, como o exemplo do Rei Eduardo I, da Inglaterra, que proibiu atividades de mineração do carvão durante as reuniões do Parlamento no século XIV, devido à intensa fumaça emitida no processo (Mostafi, Safikhani e Salehafd, 2021), foi bem mais recentemente que os impactos diretos da expansão dos processos industriais e do surgimento de novas fontes de poluentes começaram a ser estudados de forma profunda.

De acordo com Raposo Junior, Norton e Assis (2021), a falta de um acompanhamento adequado dos possíveis danos que o acúmulo de poluentes poderia causar no ambiente e na saúde humana levaram aos primeiros episódios modernos, com cobertura midiática, de mortalidade relacionada à contaminação atmosférica em cidades da Europa e dos Estados Unidos. Provavelmente o primeiro desses eventos foi o episódio belga do Vale de Meuse, em 1930, em que a soma de fatores ambientais e da poluição colaboraram para uma inversão térmica de cerca de cinco dias, o suficiente para causar mortes e adoecimento em vários indivíduos, seguido por evento semelhante em Donora, na Pensilvânia, em 1948 (Saxena e Srivastava, 2020). Talvez o mais clássico episódio relacionado à poluição do ar no século XX tenha sido o evento ocorrido em Londres em dezembro de 1952 que foi associado a cerca de até doze mil óbitos após um período de acúmulo de poluentes e inversão térmica durante cerca de três dias (Fowler *et al.*, 2020).

Igualmente importante é o papel que o crescimento da atividade de transportes ao longo dos últimos 50 anos passou a ter no aumento da poluição atmosférica. A queima incompleta dos combustíveis fósseis, o aumento das frotas veiculares e o inadequado planejamento urbano que culmina com tráfego complicado e grandes congestionamentos são algumas das causas por trás desse aumento (Wallington *et al.*, 2022). Um evento de destaque foi o smog de 1943 observado nos congestionamentos de Los Angeles, que

chamou a atenção pública para os riscos associados ao ozônio troposférico pela primeira vez (Jian *et al.*, 2024). Por causa desse tipo de ocorrências, ao longo dos séculos XX e XXI, pesquisadores ao redor do mundo buscaram estabelecer as relações entre as concentrações dos poluentes e seus impactos na saúde, e embora muitas associações já estejam claras, ainda há diversas lacunas a serem preenchidas.

No continente americano o protagonismo se deu com os Estados Unidos, sendo que a partir de 1955 o Congresso Americano financiou estudos para aumento da compreensão sobre a poluição do ar. Mas, foi apenas na década de 1960 (graças ao reconhecimento internacional da problemática de poluição do ar a partir de 1967) que se criou um programa governamental com essa finalidade nos Estados Unidos, que, no entanto, não foi bem sucedido por falta de infraestrutura e planejamento estratégico (Fowler *et al.*, 2020). Devido à pressão popular e dos veículos de comunicação, ainda nos anos 1960 foi criada a Agência de Proteção Ambiental Norte-Americana (US EPA), que passou a desenvolver os estudos voltados à temática, tornando-se órgão de referência mundial no assunto e determinando, naquele momento, os principais poluentes a serem estudados: partículas totais, CO, NO₂, O₃, SO₂ e Pb (Raposo Junior, Norton e Assis, 2021).

Ao longo das décadas seguintes a EPA conduziu pesquisas envolvendo a chuva ácida e as emissões de gases sulfurados (década de 1970), estudos sobre os gases de nitrogênio e o ozônio (1988), e, durante a prolífica década de 1990: alternativas para substituição dos compostos halogenados como clorofluorcarbonos - CFCs (1992), avaliação de risco associado ao tabagismo (1992), tecnologias de mitigação das emissões de radônio (1994), padrões de qualidade do ar quanto ao material particulado (1997), métodos de medição do material particulado fino (1998), estabelecimento dos modelos de qualidade do ar - *Community Multi-scale Air Quality (CMAQ) Modeling System* (1998) (EPA, 2022). A partir dos anos 2000 a EPA passou também a direcionar seus esforços na compreensão dos mecanismos de aquecimento global e mudanças climáticas, criação de tecnologias limpas e aperfeiçoamento dos sistemas de monitoramento, inclusive trazendo conclusões recentes como as de que, independentemente de fatores como renda e localização geográfica, as pessoas não-brancas são as mais afetadas pela poluição do ar nos Estados Unidos (EPA, 2022).

No Brasil, seguindo as tendências mundiais, foi promulgado o Decreto-Lei 303/1967, marco das preocupações ambientais, que declarava em seu terceiro artigo que substâncias emitidas por qualquer meio (industrial, agropecuário, maquinários, veículos

etc.) só poderiam ser liberadas para a atmosfera se ela não se tornasse poluída. Contudo, essa norma, de caráter meramente legislativo, demonstrou o grande despreparo de seus elaboradores diante da inexistência de meios para seu cumprimento, à época, sendo revogada sete meses mais tarde pela Política Nacional de Saneamento, estabelecida pela Lei 5318/1967 (Arantes, 2018).

A Política Nacional do Saneamento consiste em um instrumento, ainda vigente, que embora não seja uma verdadeira legislação ambiental, foi e ainda é utilizado para instrumentalizar diversas iniciativas na área. Anos mais tarde, em 1975, lançou-se o Decreto-Lei 1413, também em vigência, que indústrias instaladas no território brasileiro estão obrigadas a tomar medidas para prevenção e mitigação de contaminações ambientais, inclusive com suporte governamental (Arantes, 2018). No entanto, é nas décadas de 1980 e 1990 que o Brasil realmente define seus marcos regulatórios mais importantes, sendo um deles a Lei 6.938/81 que instituiu a Política Nacional do Meio Ambiente voltada para a preservação, conservação e melhoria dos recursos naturais, e contribuiu para criação do Conselho Nacional do Meio Ambiente – CONAMA (em seu art. 6º, I) mais tarde convertido em órgão consultivo e deliberativo pela Lei 8.028/1990, e assumindo o papel de elaborar normas e critérios para os padrões de qualidade ambiental no país, através de recursos fiscalizatórios (Valadão *et al.*, 2022).

Arantes (2018) ainda pontua que ao longo dos anos a Política Nacional do Meio Ambiente foi sendo atualizada, pela inclusão de parceiros como o Instituto Chico Mendes de Conservação da Biodiversidade (ICMBio), como órgão executor das políticas e diretrizes governamentais (Lei 11.516/2007) e o Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA), incluído pela Lei 12.856/2013 (art. 6º, IV), mas, segue apresentando deficiências e fragilidades muito grandes devido aos conflitos de interesse entre os mecanismos de proteção e os atores dos processos produtivos que demandam a utilização de cada vez mais recursos.

Abordando diretamente a poluição atmosférica, o CONAMA publicou a Resolução nº. 05 de 1989 que criou o Programa Nacional de Controle da Qualidade do Ar – PRONAR, com a finalidade de fixar os limites de emissões por fontes de poluentes a fim de garantir que ocorresse o desenvolvimento socioeconômico, contudo de maneira segura. A Resolução nº. 03 de 1990 viria a definir os padrões nacionais de qualidade do ar (*National Air Quality Standards – NAQS*), trazendo importante contribuição para o processo de avaliação e controle dos níveis de poluição, mas que devido ao crescimento populacional, industrial e veicular rapidamente se desatualizaram (Siciliano *et al.*, 2020).

Apenas em novembro de 2018, quase 30 anos após o lançamento dos primeiros padrões, o CONAMA lançou a Resolução nº. 491, baseada nos NAQS promulgados como metas pela OMS ainda em 2005 (Siciliano *et al.*, 2020).

Essa nova resolução trouxe um processo de quatro etapas, escalonadas e evolutivas, visando que estados e o Distrito Federal estabelecessem planos de redução progressiva de suas emissões ao longo do tempo. Nesse contexto, o Padrão Intermediário 1 (PI-1) representa o valor inicial a ser implementado pelos estados. Avaliações técnicas baseadas em modelos atmosféricos devem guiar a estipulação dos demais padrões intermediários, com o objetivo de atingir o Padrão Final (PF), algo ainda não consolidado. A Tabela 1 apresenta os níveis de quantificação atualmente presentes na legislação brasileira para os diferentes poluentes para a avaliação qualitativa do ar.

Tabela 1 – Parâmetros estabelecidos para avaliação da qualidade do ar conforme a Resolução CONAMA N° 491 de 19/11/2018.

Poluente Atmosférico	Sigla	Período de Referência	PI-1	PI-2	PI-3	PF	ppm
			($\mu\text{g}/\text{m}^3$)	($\mu\text{g}/\text{m}^3$)	($\mu\text{g}/\text{m}^3$)	($\mu\text{g}/\text{m}^3$)	
Material Particulado	MP ₁₀	24 horas	120	100	75	50	-
		Anual ¹	40	35	30	20	-
Material Particulado	MP _{2,5}	24 horas	60	50	37	25	-
		Anual ¹	20	17	15	10	-
Dióxido de Enxofre	SO ₂	24 horas	125	50	30	20	-
		Anual ¹	40	30	20	-	-
Dióxido de Nitrogênio	NO ₂	1 horas ²	260	240	220	200	-
		Anual ¹	60	50	45	40	-
Partículas Totais em Suspensão	PTS	24 horas	-	-	-	240	-
		Anual ⁴	-	-	-	80	-
Fumaça	-	24 horas	120	100	75	50	-
		Anual ¹	40	35	30	20	-
Ozônio	O ₃	8 horas ³	140	130	120	100	-
Monóxido de Carbono	CO	8 horas ³	-	-	-	-	9
Chumbo	Pb ⁵	Anual ¹	-	-	-	0,5	-

Fonte: IEMA, 2022 (<https://iema.es.gov.br/qualidadedoar/legislacao>). Legenda: 1 - Média aritmética anual. 2 - Média horária. 3 - Máxima média móvel obtida no dia. 4 Média geométrica anual. 5 Medido nas partículas totais em suspensão. Partes por milhão (ppm).

Em 22 de setembro de 2021, a OMS lançou novos NAQS em atualização às definições de 2005, com níveis ainda mais rigorosos para os poluentes (exceto o SO₂),

que podem ser verificados na Figura 2. Esses novos valores demonstram que o Brasil se encontra num cenário de ampla defasagem em relação aos níveis preconizados internacionalmente. A falta de marcos temporais claros para o alcance das metas determinadas pelo CONAMA também gera insegurança e incerteza sobre o quanto tem se avançado nesse sentido, favorecendo a percepção muitas vezes incipiente de diversos agentes sociais sobre os riscos de adoecimento e degradação ambiental a que se sujeitam (De Simoni *et al.*, 2021).

Em tempo, é válido pontuar que em 03/05/2024 foi sancionada a nova Lei 14.850/2024 que cria a Política Nacional de Qualidade do Ar (Agência Câmara de Notícias, 2024). Um dos aspectos marcantes dessa nova legislação está justamente na instituição de mecanismos para o monitoramento da qualidade do ar no Brasil e a divulgação desses dados para a população.

Essa nova Lei também prevê a criação de um inventário nacional de emissões contendo as principais fontes de emissões atmosféricas, poluentes inventariados e a distribuição geográfica das emissões por regiões. Tendo como base este inventário, a União, através do Ministério do Meio Ambiente e Mudança do Clima (MMA) terá a missão de elaborar o Plano Nacional de Gestão da Qualidade do Ar, a ser atualizado a cada quatro anos. Os desfechos da implementação dessa legislação refletirão diretamente no futuro da qualidade do ar no território brasileiro.

Figura 2 – Novos parâmetros de qualidade do ar estabelecidos pela OMS em 2021.

NOVOS PARÂMETROS DE QUALIDADE DO AR			
Organização Mundial da Saúde			
Poluente	Período de referência	2005 AQGs	2021 AQGs
PM _{2.5} µg/m ³ 	Anual 24 horas	10 25	5 15
PM ₁₀ µg/m ³ 	Anual 24 horas	20 50	15 45
O ₃ µg/m ³ 	Alta temporada 8 horas	- 100	60 100
NO ₂ µg/m ³ 	Anual 24 horas	40 -	10 25
SO ₂ µg/m ³ 	24 horas	20	40
CO mg/m ³ 	24 horas	-	4
AQGs – Diretrizes de Qualidade do ar			

Fonte: Elaboração própria.

2.7 Avaliação do impacto em saúde

Diante do cenário de que os poluentes atmosféricos estão diretamente envolvidos com o adoecimento e com danos ambientais, sendo capazes de afetar desde a microbiota intestinal (Feng *et al.*, 2020) até favorecer o desenvolvimento de patologias crônico-degenerativas (Marabotti *et al.*, 2017), alguns impasses surgiram no meio científico sobre como seguir adiante nesse ramo de conhecimento, evitando a repetição de resultados e trazendo abordagens realmente inspiradoras.

Assim sendo, foram desenvolvidas as metodologias quantitativas de avaliação de risco e impacto à saúde (*Health Impact Assessment* – HIA). Essas estratégias, como a de avaliação em espaços urbanos (*built environment* – BE) foram primeiro exploradas em países altamente desenvolvidos, mas logo se percebeu a necessidade de realizar avaliações em países subdesenvolvidos, onde as taxas de urbanização, crescimento populacional e crescimento da frota veicular, por exemplo, são muito mais aceleradas (Thondoo *et al.*, 2022), como ocorre em diversas cidades brasileiras.

Essas ferramentas possuem aplicações muito úteis para a melhoria dos processos governamentais e para a tomada de decisões com relação às iniciativas em saúde pública, sendo que Abe e Miraglia (2018) apontam que no Brasil, o emprego de um processo padronizado e bem estruturado, poderia reduzir consideravelmente os efeitos adversos à saúde oriundos de políticas públicas mal desenhadas que geralmente não calculam de maneira adequada os impactos de médio e longo prazo. Nothaft, Linzalone e Busato (2020) ressaltam que a produção científica em território brasileiro utilizando HIA (semelhantemente ao que vêm ocorrendo na América Latina como um todo) embora em expansão, é incipiente, tendo sido produzido o primeiro documento em nível nacional apenas no ano de 2014 (Avaliação de Impacto à Saúde - AIS: metodologia adaptada para aplicação no Brasil), enquanto a OMS já havia produzido documentos semelhantes no ano de 2005.

Considerando que a Organização Panamericana de Saúde declarou que a poluição do ar constitui uma crise global em saúde pública e que no Brasil as mortes ligadas à poluição ambiental persistem (a poluição atmosférica pode chegar a superar em cinco vezes o tabagismo passivo em número de mortes) (OPAS, 2021), pode-se afirmar que o Brasil faz parte da lista de países que carece de estudos mais aprofundados na temática, especialmente considerando as características particulares de suas regiões, tão diferentes

entre si (Dapper, Spohr e Zanini, 2016). Tais investigações tem a capacidade de proporcionar recursos para redução da morbimortalidade relacionada às doenças cardiorrespiratórias (mais frequentes desfechos ligados à poluição do ar), bem como os inúmeros impactos financeiros delas decorrentes (Pereira Barboza *et al.*, 2022).

Na Tabela 2, pode-se verificar as concentrações dos poluentes relacionadas aos diferentes índices de qualidade do ar. Considerando que a poluição atmosférica, embora ubíqua, não é um fenômeno “democrático” como se pensava outrora, diferentes indivíduos sofrem reveses muito distintos dentro de um mesmo cenário de alteração qualitativa, e, sendo assim, idade, sexo, comorbidades e renda são fatores que vêm sendo explorados de maneira específica nas avaliações mais recentes (Pamplona *et al.*, 2020; Carvalo *et al.*, 2021).

Tabela 2 – Índices de qualidade do ar e efeitos à saúde conforme a Resolução CONAMA N° 491 de 19/11/2018.

Índice		MP ₁₀ (µg/m ³) 24h	MP _{2,5} (µg/m ³) 24h	O ₃ (µg/m ³) 8h	CO (ppm) 8h	NO ₂ (µg/m ³) 1h	SO ₂ (µg/m ³) 24h
Classe	Valor						
Boa	0 - 40	0 - 50	0 - 25	0 - 100	0 - 9	0 - 200	0 - 20
Moderada	41 - 80	>50 - 100	>25 - 50	>100 - 130	>9 - 11	>200 - 240	>20 - 40
Ruim	81 - 120	>100 - 150	>50 - 75	>130 - 160	>11 - 13	>240 - 320	>40 - 365
Muito ruim	121 - 200	>150 - 250	>75 - 125	>160 - 200	>13 - 15	>320 - 1130	>365 - 800
Péssima	201 - 400	>250 - 600	>125 - 300	>200 - 800	>15 - 50	>1130 - 3750	>800 - 2620

Fonte: IEMA, 2022 (<http://energiaeambiente.org.br/qualidadedoar>) adaptado.

A tabela 3 evidencia alguns impactos à saúde humana possivelmente verificados nas condições em que a qualidade do ar se desvia dos padrões adequados. Esses desfechos são úteis para compreender as principais reações que a média dos indivíduos poderá apresentar nos variados cenários. O uso dessa ferramenta para nortear ações preventivas em episódios críticos já se mostrou positivo já que a emissão de alertas de má qualidade do ar parece ser um agente sensibilizador para a população (Mirabelli, Ebelt e Damon, 2020), porém no Brasil essa informação ainda não se encontra disponível em tempo real

para a maioria dos municípios devido ao incipiente monitoramento da qualidade do ar (Vormittag *et al.*, 2021). Com isso, fica comprometido tanto seu uso, como também seu entendimento por parte da população em geral.

Tabela 3 – Impactos à saúde verificados em condições de desvios na qualidade do ar.

Qualidade	Índice	Desfecho
N1 – Boa	0 – 40	Praticamente não há risco.
N2 – Regular	41 – 80	Grupos sensíveis (crianças, idosos, portadores de doenças cardiorrespiratórias) podem apresentar tosse e cansaço. População em geral não costuma ser afetada.
N3 – Inadequada	81 – 120	Nível de atenção - Toda a população pode apresentar sintomas como tosse seca, cansaço, ardor nos olhos, nariz e garganta. Pessoas de grupos sensíveis podem apresentar efeitos mais sérios na saúde.
N4 – Má	121 - 200	Nível de alerta - Toda a população pode apresentar agravamento dos sintomas como tosse seca, cansaço, ardor nos olhos, nariz e garganta e ainda apresentar falta de ar e respiração ofegante. Efeitos ainda mais graves à saúde de grupos sensíveis.
N5 – Péssima	201 - 400	Nível de emergência - Toda a população pode apresentar sérios riscos de manifestações de doenças cardiorrespiratórias. Aumento de mortes prematuras em pessoas de grupos sensíveis.
N6 – Crítica	Acima de 400	

Fonte: IBRAM, 2022 (<https://www.ibram.df.gov.br/wp-content/uploads/2018/03/IQAR-utilizado-pelo-IBRAM.pdf>) adaptado.

2.8 Aumento da temperatura e o adoecimento

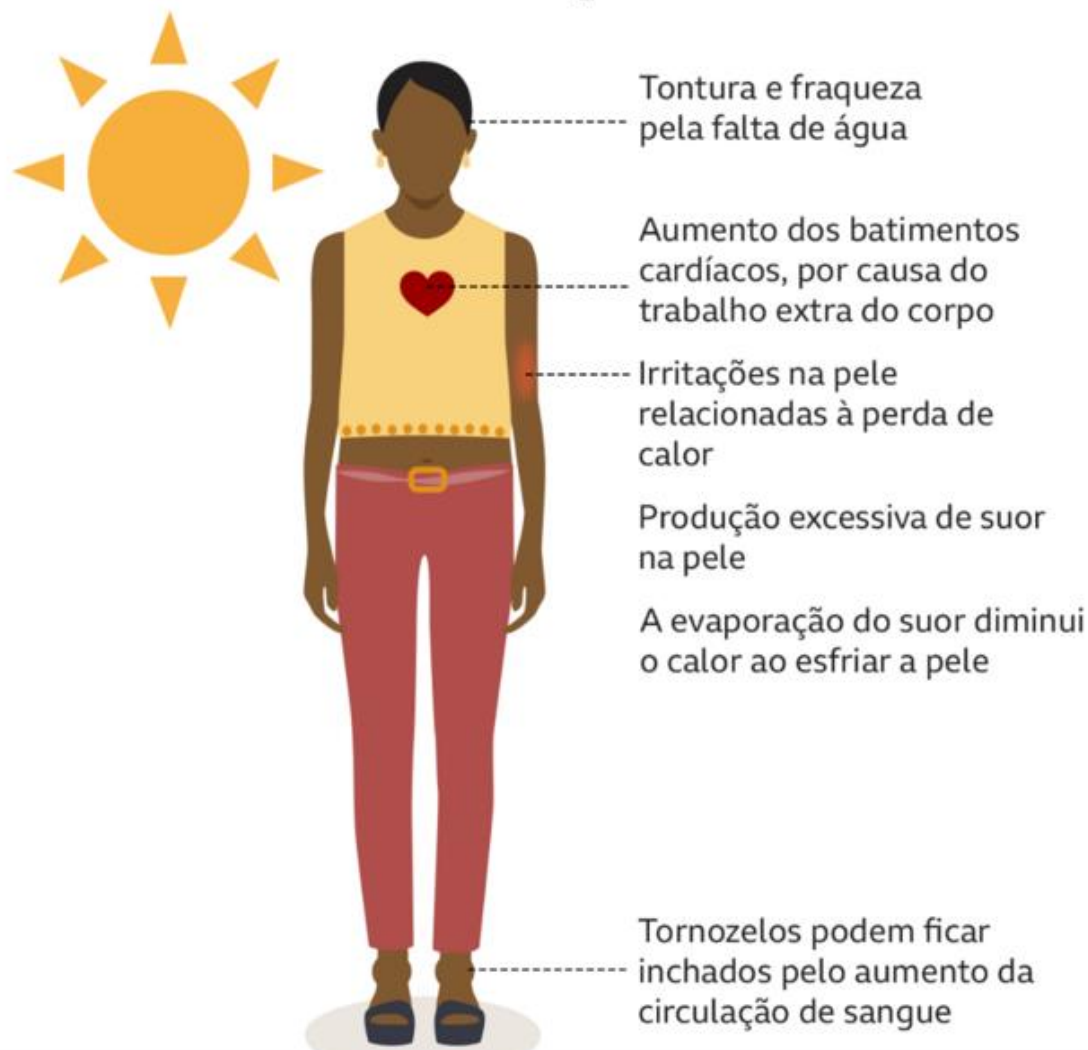
É igualmente necessário evidenciar os impactos à saúde humana provocados pelas mudanças climáticas, com especial destaque para os efeitos provocados pelo aumento de temperatura (Figura 3). Investigações consistentes têm demonstrado que os efeitos do calor excessivo podem ser tão abrangentes quanto os da poluição atmosférica, inclusive intensificando os agravos provocados por ela, de maneira sinérgica.

Ebi *et al.* (2021) apontaram que a condição de estresse provocada pelo aumento de temperatura está diretamente relacionada com o aumento de morbimortalidade populacional. Esses autores revelam que aproximadamente metade da população mundial e mais de um bilhão de trabalhadores estão expostos a condições extremas de temperatura, acarretando efeitos negativos sobre sua saúde. O absenteísmo no trabalho, por exemplo, é uma das consequências das ondas de calor (Shuang *et al.*, 2019). Esta é uma grande problemática que além de ter efeitos diretos sobre o desempenho e a produtividade da população economicamente ativa, impacta a produção de bens e riqueza de uma região ou país, dificultando seu desenvolvimento. O absenteísmo escolar também já foi apontado como consequência do aumento de temperatura, uma vez que esse fenômeno é capaz de afetar a capacidade cognitiva e o comportamento de crianças e adolescentes (Keivabu, 2024).

No que concerne à saúde, vários tipos de doenças podem ser agravados ou provocados pela exposição a temperaturas extremas e ondas de calor, sendo as populações de regiões tropicais as mais vulneráveis a esses aumentos. Alterações do fluxo sanguíneo, do ritmo cardíaco e risco aumentado de acidentes vasculares cerebrais (Cheng e MacDonald, 2019); agravamento de doenças cardiorrespiratórias e hipertensão (Requia *et al.*, 2024); desidratação, tontura, debilidade e doenças renais agravadas pela intensa transpiração (Chapman *et al.*, 2021); alterações da pele (Hui-Beckman *et al.*, 2023); risco aumentado de neoplasias (Hiatt e Beyeler, 2020); alterações gestacionais (Olson and Metz, 2020) e doenças mentais (Lawrance *et al.*, 2021), estão entre os agravos em saúde que tendem a se tornar cada vez mais frequentes com o aquecimento global.

Figura 3 – Alguns efeitos do calor sobre a saúde.

Como o calor afeta o corpo



Fonte: Serviço de Saúde Pública da Inglaterra



Fonte: BBC News, 2022. (<https://www.bbc.com/portuguese/geral-62009179>)

2.9 Histórico regional da área de estudo

Os estados de Mato Grosso e Mato Grosso do Sul formavam um único território até o ano de 1977, quando ocorreu sua separação. A história de Mato Grosso é bastante antiga, sendo que as primeiras incursões ao território que hoje compreende o estado ocorreram já por volta de 1525. Ao longo de sua história, o Estado passou por diversas modificações sendo alvo de disputa entre portugueses e espanhóis, incursões bandeirantes, palco de intensa exploração para retirada de minérios e até movimentos separatistas. A origem do nome do Estado veio através dos irmãos Paes de Barros,

impressionados com as “sete léguas de mato” ao redor das minas descobertas em 1734 (Mato Grosso, 2022).

A partir das décadas de 1960 e 1970 ocorreu um processo de ocupação territorial anômalo, com a abertura de diversas pequenas propriedades focadas em produção rudimentar de subsistência. Paralelamente, iniciou-se também o fornecimento de incentivos fiscais para a abertura das primeiras grandes pastagens. Pressões internacionais para atendimento das demandas de modernização das regiões Sul e Sudeste do Brasil levaram à urbanização bem mais intensa da região nas décadas que se seguiram, com expansão acelerada do agronegócio e também das desigualdades sociais e impactos ambientais chegando ao cenário atual em que uma das maiores questões regionais está ligada à logística da exportação dos bens (*commodities*) produzidos, na tentativa de evitar o uso de rodovias para essa finalidade, visando um escoamento mais seguro, facilitado e financeiramente vantajoso (Rocha e Saes, 2018).

Geograficamente, o estado está localizado entre a Linha do Equador e o Trópico de Capricórnio, onde as temperaturas são costumeiramente mais elevadas, com estação seca e chuvosa predominantes em detrimento das estações mais bem definidas das regiões temperadas. Nos últimos anos, o surgimento de focos de calor intenso vem se deflagrando na região, ligados a estiagens cada vez mais longas e severas, facilitando o início de graves incêndios, muitas vezes de origem criminosa, conforme aponta o Centro Nacional de Monitoramento e Alertas de Desastres Naturais (CEMADEN, 2018), além de estudos demonstrarem que o aumento de temperatura está ligado ao adoecimento, como doenças de ordem mental e comportamental, por exemplo (Silva *et al.*, 2020; Lu, 2020).

Em 2001, com a criação do Programa de Vigilância em Saúde de Populações Expostas à Poluição Atmosférica – VIGIAR, no contexto da Secretaria de Vigilância em Saúde do Ministério da Saúde do Brasil – SVS/MS, objetivou-se a aplicação de um conjunto de ações adotadas pelas autoridades competentes no sentido de reduzir e os agravos à saúde provocados pela poluição atmosférica. Apesar disso até a presente data o Mato Grosso não estabeleceu em sua legislação os planos próprios de avaliação e mitigação dos impactos à qualidade do ar conforme estabelecido nas atualizações do CONAMA em 2018, nem sequer possui estações ativas de verificação de qualidade do ar em tempo real (De Simoni *et al.*, 2021).

Importantes estudos já foram anteriormente desenvolvidos em algumas regiões do Mato Grosso no que concerne a quantificações dos níveis de poluição atmosférica e seus possíveis impactos à população. Os resultados obtidos já demonstraram que

concentrações aumentadas do PM_{2,5} estiveram associadas ao aumento de internações por doenças respiratórias em crianças menores de 5 anos, na cidade de Cuiabá (Silva *et al.*, 2013), ao sul do estado, e na cidade de Alta Floresta, município da região norte (Carmo *et al.*, 2010). De forma similar, Ignotti *et al.* (2010) já havia observado efeito semelhante do PM_{2,5} nas hospitalizações de crianças e idosos com quadros respiratórios em períodos de seca, na cidade de Alta Floresta.

O grupo liderado por Sandra Hacon junto à Universidade do Estado de Mato Grosso (UNEMAT) também observou associação entre os níveis de CO e material particulado e o baixo peso ao nascer nas microrregiões de Tangará da Serra e Alta Floresta (Candido da Silva *et al.*, 2014). Mais recentemente, Rodrigues *et al.* (2017) em seu estudo ecológico com moradores das cidades de Cuiabá e Várzea Grande, demonstrou que o PM_{2,5} está associado à morbimortalidade por doenças cardiovasculares e seus efeitos podem ser potencializados pelo calor, pela baixa umidade e durante a estação seca. Isso ressalta a influência das variações climáticas sobre os desfechos ligados à poluição (Fernandes, Hacon e Novais, 2021).

Essas evidências destacam que os impactos à saúde provocados pela poluição atmosférica fazem parte do cotidiano dos residentes de diversos municípios de Mato Grosso. Tal percepção aponta para a necessidade de estudos que aprofundem a temática, e a microrregião de Sinop ainda não foi contemplada nessas investigações. Ademais, poucos estudos no Brasil investigaram a sinergia entre as mudanças climáticas e a poluição.

3. JUSTIFICATIVA

A poluição do ar representa um impacto direto à saúde humana, que há pelo menos quatro décadas vem chamando a atenção de agências regulatórias na busca por legislar os níveis de emissão de substâncias potencialmente tóxicas para a atmosfera. Embora existam vários materiais orientativos e pesquisas atestando os riscos relacionados a esse tipo de contaminação, pouco foi feito no Brasil no sentido de realmente implementar mecanismos de minimização de tais agravos à saúde da população (Silva e Vieira, 2017).

O Estado de Mato Grosso, terceiro maior em extensão territorial do país, já foi uma referência nos modelos de avaliação da qualidade do ar, até por volta do final dos anos 2000. Apesar disso, já há alguns anos não ocorre um monitoramento adequado da

qualidade do ar, havendo várias lacunas ou desencontros de informações, mesmo nos dados fornecidos pelas entidades de monitoramento ambiental, como a SEMA/MT.

Ademais, a região norte do estado, na qual se localiza o município de Sinop, é digna de nota no que concerne aos estudos de qualidade do ar, já que destoa das grandes metrópoles ao não apresentar grande poluição de origem industrial, mas que, em contrapartida, enfrenta as consequências de um clima mais quente e seco durante grande parte do ano (sazonalidade), além dos frequentes e graves incêndios florestais que se deflagram na região e da forte expansão do agronegócio (Töpfer, Coy e Zirkl, 2020). É importante ressaltar que estudos recentes apontam que a exposição à poluição atmosférica vivenciada em pequenas e médias cidades pode ser inclusive mais intensa que em grandes metrópoles (Squizzato *et al.*, 2021; Silva Júnior *et al.*, 2023).

Além disso, por estar localizada na região conhecida como Arco do Desmatamento, no encontro entre os biomas Amazônico e Cerrado, Sinop está num local muito estratégico para estudos ambientais. Esses biomas têm se revezado continuamente no ranking dos mais afetados pela ação de incêndios florestais, sendo que reduções observadas nas emissões provenientes de incêndios na Amazônia, são rapidamente suprimidas pela aceleração das emissões no Cerrado, impedindo evoluções na qualidade do ar em contexto regional (Pope *et al.*, 2019). O estudo desenvolvido por Oliveira *et al.* (2023) com dados de poluição atmosférica da região Amazônica e da região Centro-Oeste entre 2010 e 2019, constatou, de forma alarmante, que cerca de 60% da população dessa região está exposta a condições inadequadas de qualidade do ar por pelo menos seis meses do ano.

Até o momento, a maior parte dos estudos se dedicou a avaliar a qualidade do ar em cidades que estejam dentro do eixo Sudeste-Sul no Brasil, sendo em muitos aspectos já consideravelmente desatualizada a produção feita sobre cidades da região Centro-Oeste. Diante disso, existem hiatos na avaliação da qualidade do ar em muitos municípios de destaque e em franco crescimento na região Centro-Oeste, sendo importante a construção do conhecimento a respeito dessas condições, em vistas de alertar os possíveis riscos existentes e atingir melhor qualidade de vida às suas populações.

4. OBJETIVOS

4.1 Geral

Investigar os impasses sociopolíticos e os impactos à saúde relacionados à poluição atmosférica e às mudanças climáticas em uma cidade Amazônica, no Centro-Oeste do Brasil.

4.2 Específicos

- Discutir as repercussões da poluição atmosférica e das mudanças climáticas na busca pelo desenvolvimento sustentável;
- Quantificar os níveis dos principais poluentes atmosféricos (O_3 , $PM_{2,5}$ e PM_{10}) e seu enquadramento junto às diretrizes nacionais e internacionais vigentes;
 - Analisar o impacto de episódios de incêndios sobre a dinâmica dos poluentes;
 - Verificar a associação entre os níveis dos diferentes poluentes com os possíveis desfechos climáticos e em saúde.

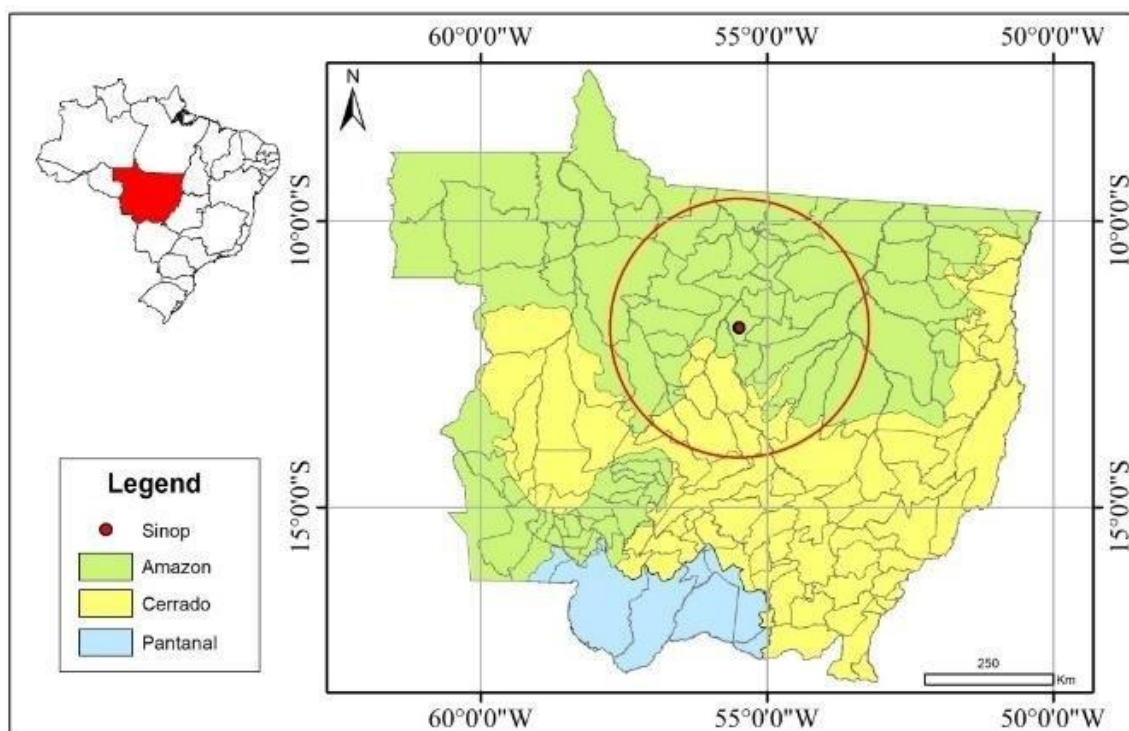
5. MATERIAL E MÉTODOS

5.1 Área de estudo

O presente estudo foi desenvolvido em uma cidade da região Centro-Oeste, Sinop, maior cidade da região norte do Mato Grosso (Figura 4). Este município possui uma área territorial de aproximadamente 3.991 km², uma população de quase 200 mil habitantes (IBGE, 2022) e seu índice de desenvolvimento humano (IDH) municipal é de 0,754, classificando-se como IDH alto. Com apenas 49 anos de fundação, Sinop já é a quarta maior cidade do Mato Grosso em termos populacionais e econômicos.

Sinop também é considerada uma cidade polo tanto na prestação de serviços, como também para a áreas da saúde e educacional, por contar com diversas escolas públicas e privadas, e ainda pela presença dos *campi* da Universidade Federal de Mato Grosso – UFMT, da Universidade do Estado de Mato Grosso – UNEMAT e do Instituto Federal de Mato Grosso – IFMT, além de outras faculdades e institutos privados. Dados apontam que moradores de mais de mais 50 municípios da macrorregião e advindos do sul do estado do Pará acorrem à cidade para essas finalidades, perfazendo um público de mais de 1 milhão de pessoas (FAMATO, 2022). Sinop localiza-se a cerca de 500 km da capital do estado, Cuiabá (Sinop, 2023).

Figura 4 – Mapa da cidade de Sinop, estado de Mato Grosso.

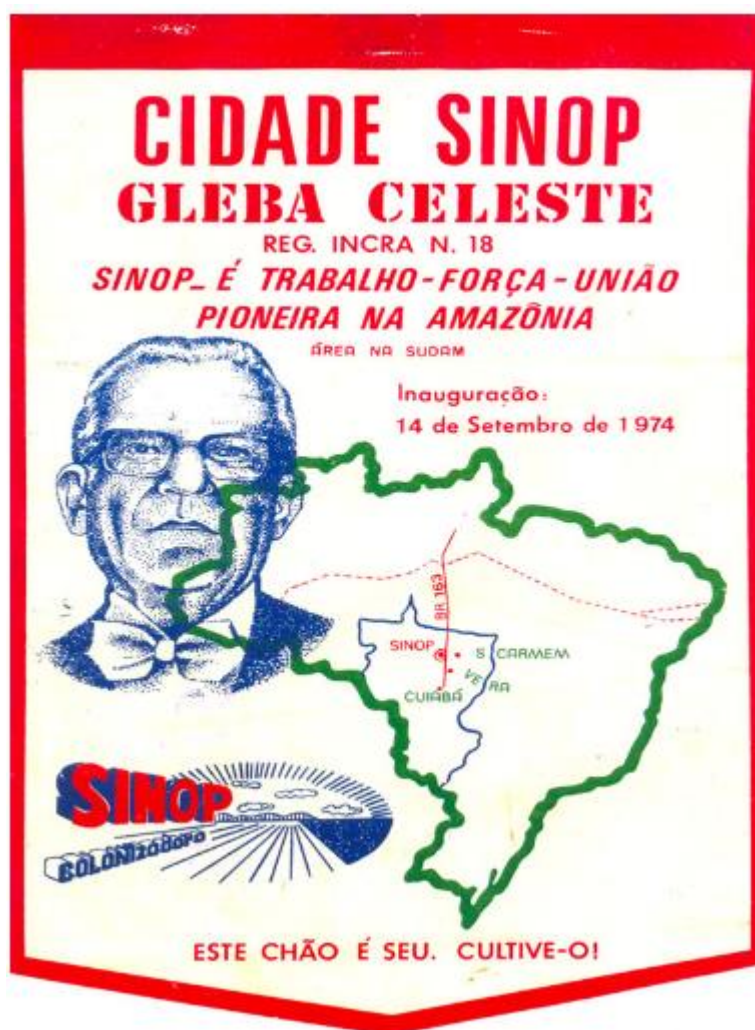


Fonte: Martim *et al.*, 2020

(<https://ojs.ufgd.edu.br/index.php/rbclima/article/view/14231/7457>).

O surgimento de Sinop é uma consequência da Política de ocupação da Amazônia Legal Brasileira, deflagrada pelo Governo Federal durante a década de 1970. As famílias pioneiras chegaram à região em que hoje se localiza a cidade entre 1972 e 1973, e, em sua maioria, eram oriundas dos estados da região sul do país (IBGE, 2022). A área original de aproximadamente 6.450 km² era denominada de Gleba Celeste, e foi rapidamente desmembrada em diversas propriedades privadas (sítios e fazendas) e desmatada para o surgimento das primeiras formações urbanas (Ioris, 2017). A figura 5 apresenta um cartaz do período de colonização da cidade. Durante várias décadas a produção madeireira foi o grande propulsor econômico da região, atendendo as demandas das regiões sul, sudeste e exportações, até esse formato entrar em crise a partir do início dos anos 2000 (Simão e Bampi, 2020).

Figura 5 – Cartaz de inauguração da cidade de Sinop, na década de 1970.



Fonte: Ioris, 2017. (<https://www.tandfonline.com/doi/abs/10.1111/gere.12222>).

Sinop também está situada às margens da rodovia federal BR-163, popularmente conhecida como rodovia Cuiabá-Santarém. Essa rodovia é um marco da intensa expansão agrícola na região, sendo um dos maiores corredores de escoamento de soja e outras *commodities* para o porto de Santarém (Gollnow *et al.*, 2018; Coelho *et al.*, 2021), no estado do Pará, localizado a cerca de 1.400 km ao norte de Sinop. Fearnside (2007) já ressaltava há quase 20 anos que a construção de rodovias, como a BR-163, adentrando em áreas de florestas é um processo muito impactante e cujas etapas não raramente se distanciam de uma perspectiva sustentável, especialmente nas regiões tropicais.

Do ponto de vista ambiental, Sinop está na faixa de transição entre o Cerrado e a Amazônia, um local que sofre intensas pressões devido às transformações de origem antropogênica dentre elas o desmatamento, o descontrole na dinâmica dos incêndios

florestais, o uso de pesticidas e os consequentes efeitos climáticos dessas práticas (Silva *et al.*, 2019; Amaral e Silva, 2020). Não obstante, Sinop possui uma usina hidrelétrica instalada no rio Teles Pires. De acordo com Lucanus *et al.* (2021), barragens de usinas hidrelétricas são uma ameaça grave aos rios da bacia Amazônica, e inclusive contribuem para a emissão de gases de efeito estufa. Esses mesmos autores, detectaram níveis aumentados de CH₄ na barragem de Sinop.

Notícias recentes têm apontado para problemáticas que estão se tornando comuns na região: deterioração da qualidade do ar, aumento populacional, aumento do fluxo de veículos pesados e surgimento de ilhas de calor (Globo, 2018; Globo, 2020; Pereira, Muniz e Oliveira Júnior, 2020). Considerando ainda que, segundo a classificação de Köppen-Geiger, o clima de Sinop é denominado de tropical de savana ou Aw (Magalhães *et al.*, 2019), marcado por estação chuvosa e intensa estação quente e seca, forma-se um cenário de interesse para a avaliação de potenciais agravos em saúde.

5.2 Dados da poluição ambiental, meteorológicos e de incêndios florestais

As medições das concentrações dos poluentes foram obtidas através dos dados de satélite fornecidos pelo Centro Europeu de Previsões Meteorológicas de Médio Prazo (ECMWF) “*Copernicus Atmospheric Monitoring Service*”, através do aplicativo denominado *The Weather Channel* (IBM, Estados Unidos da América), metodologia empregada também por Leão e colaboradores (2021).

Para a devida comparação dos níveis de poluentes obtidos, foram utilizadas a Resolução 491/2018 do CONAMA, última legislação tratando do assunto a ser emitida em nosso país, bem como as definições atualizadas da OMS em 2021, que decidiu, para a maioria dos poluentes, estabelecer limites mais rigorosos que os que definira em 2005, sinalizando a preocupação com a temática e os avanços da poluição mundial (Rocha, 2021).

Dados climáticos, incluindo temperatura média diária (°C), velocidade do vento (m/s), umidade (%), pressão atmosférica (hPa), índice de radiação ultravioleta e precipitação (mm), foram coletados a partir de uma estação automatizada em Sinop (11°87' S, 55°57' W), a uma altitude de 370 metros. Esses dados foram obtidos através do sistema de monitoramento agrometeorológico (Agritempo) desenvolvido pela Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA) em colaboração com o Instituto Nacional de Meteorologia (INMET) do Brasil (Agritempo, 2023). Trata-se de uma

plataforma online que oferece aos usuários acesso às informações meteorológicas e agrometeorológicas de diferentes municípios e estados do Brasil (Carvalho et al., 2017).

Além disso, foram coletados dados sobre incêndios florestais utilizando a ferramenta “Queimadas” mantida pelo Instituto Nacional de Pesquisas Espaciais (INPE) do Brasil. Esses dados incluem a data, latitude e longitude de cada incêndio florestal (pixels “queimados”) e o número de fontes de fogo identificadas (focos de incêndio). Eles também fornecem a potência radiativa do fogo (*fire radiative power* – FRP, em inglês) em megawatts, uma medida quantificável do calor radiante emitido pelos incêndios.

O período de extração de dados foi de 22/09/2021 até 23/09/2023, totalizando dois ciclos de quatro estações, iniciando na primavera de 2021 e finalizando no término do inverno de 2023. Para a produção científica, o recorte escolhido foi de 01/01/2022 até 31/12/2022.

5.3 População e dados de saúde

Os dados demográficos e referentes à saúde populacional nas regiões supracitadas foram coletados por meio do DATASUS/Ministério da Saúde e do IBGE. Entre os dados de interesse extraídos estão os de mortalidade cardiovascular (I00-I99), bem como mortalidade por causas não-externas (A00-R99), mortalidade total da população (A00-Y98), mortalidade por doenças isquêmicas do coração (I20-I25) e mortalidade respiratória (J00-J99).

5.4 Avaliação de impacto à saúde

Avaliamos os desfechos em saúde considerando as concentrações de poluentes como equivalentes aos novos limites propostos pela OMS em 2021 (5 $\mu\text{g m}^3$ para $\text{PM}_{2.5}$, 15 $\mu\text{g m}^3$ para PM_{10} e 100 $\mu\text{g m}^3$ para O_3). Para isso, utilizamos o software AirQ+ (versão 2.2.4) estabelecido pela OMS para realizar avaliações de impacto na saúde para efeitos de longo prazo com base em tendências temporais dos poluentes. Esta ferramenta pode ser aplicada a qualquer região para avaliar até que ponto um resultado específico de saúde (em termos de mortalidade ou morbidade) é atribuível a certas concentrações de poluentes atmosféricos e os efeitos na saúde se os níveis mudarem no futuro em comparação com o presente (Wikuats et al., 2023). As mortes atribuídas à poluição

atmosférica foram obtidas com base nas equações propostas por Cakaj *et al.* (2023) e Leão *et al.* (2023).

5.5 Modelagens em aprendizado de máquina (*Machine Learning*)

A abordagem de aprendizado de máquina (*Machine learning*) foi utilizada para realizar a simulação dos cenários de aumento de temperatura, especificamente a utilização do método Support Vector Machine (SVM), que é um algoritmo supervisionado cujo propósito é classificar dados em duas ou mais categorias, tendo se popularizado na identificação de padrões, previsões climatológicas ou detecção de informações novas (Fan *et al.*, 2018; Mahalingam *et al.*, 2019). O processo de treinamento do modelo teve como base os registros diários ao longo do período de estudo, considerando diversas variáveis meteorológicas como variáveis independentes, enquanto os poluentes atmosféricos (O₃, MP_{2,5} e MP₁₀) foram tratados como as variáveis dependentes e para melhora da confiabilidade dos resultados, foi realizada a validação cruzada.

Posteriormente, foram simulados os poluentes frente aos vários cenários progressivos de aumento de meio grau de temperatura: partindo de + 0,5 °C até +4°C de aumento, e analisadas suas concentrações. A escolha desses cenários foi, no entanto, conservadora diante dos dados divulgados pelo Painel Intergovernamental sobre Mudanças Climáticas (IPCC) que apontam para aumentos de temperatura globais que podem variar entre 3,3°C e 5,7°C até 2100 (Boehm e Schumer, 2023).

5.6 Análise estatística e aspectos éticos

Após a obtenção dos dados a serem utilizados no desenvolvimento da pesquisa, foram realizadas as análises estatísticas pertinentes. O trabalho seguiu os preceitos científicos correlatos à pesquisa a ser desenvolvida, muito embora em se tratando apenas do uso indireto de informações oriundas de seres humanos (dados de saúde obtidos na plataforma DATASUS), não tenha sido necessária a submissão aos comitês de ética.

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6. MANUSCRITOS

6.1 Manuscrito I

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2030 Agenda: Discussion on Brazilian priorities facing air pollution and climate change challenges

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Abstract

The advance of human activities in a disorderly way has accelerated in recent decades, intensifying the environmental impacts directly linked to these practices. The atmosphere, essential for the maintenance of life, is increasingly saturated with pollutants, offering risks to practically all the inhabitants of the planet, a process that, in addition to causing illness and early mortality, is related to serious financial losses (including in the production of goods), dangerous temperature increase and severe natural disasters. Although this perception is not recent, the global initiative to control the different mechanisms that trigger the commitment of biodiversity and irreversible climate changes arising from pollution is still very incipient, given that global initiatives on the subject emerged just over 50 years ago. Brazil is a territory that centralizes many of these discussions, as it still faces both political and economic obstacles in achieving a sustainable growth model as it was agreed through the United Nations 2030 Agenda. Even though there is little time left for the completion of these goals, much remains to be done, and despite the fulfillment of this deadline, the works will certainly need to be extended for much longer until an effective reorientation of consciousness occurs. Scientific research and discussions are fundamental tools to the understanding of issues still little explored in this field.

Keywords: Contamination. Heat waves. Latin America. One Health. Sustainable Development Goals. Wildfires.

Introduction

Recently, in Europe, it was released a final report listing several concerns related to climate change, the environment, and global health, which in the next decade should motivate research and the development of technologies in the context of the European Union, and as an extension, the whole world (Dravkik et al. 2022). In this sense, air pollution (and its relationship to local climates) is a fundamental concern because it centralizes several of these issues. People's physical and mental health, economic and

social progress, the overall image of the cities, as well as people's livelihood and happiness index are all affected by the quality of the atmosphere. In the last decades, as people's living standards have risen and environmental consciousness has grown, air pollution has emerged as a severe environmental issue that has sparked widespread concern. As a result, conserving and improving the environment has become a top priority for the entire society.

According to Haq et al. (2021), the establishment of the 2030 Agenda by the United Nations in 2015, with its 17 SDGs, 169 targets and more than 200 indicators related to the different global challenges in the search for reducing inequalities, environmental impacts and sustainable technologies, many countries have been taking actions in the quest to fit into these proposals, with some frequency adapting them according to the most critical needs of each location. Although many theorists criticized the 2030 Agenda for having too many goals and lacking prioritization, as mentioned by Rocha and Alexandre Weiss (2019), unfortunately, air pollution was one issue that was deemphasized. Air pollution's position in SDGs is cloudy and, while climate change was highlighted in one of the goals (SDG13), there is no headline goal on air pollution. Air pollution is specifically cited in 3 targets, under health (SDG3), sustainable cities (SDG11), and responsible consumption (SDG12) but shares these targets with other issues. However, a broad perspective illustrates that air pollution is linked in principle to most of the SDGs, either in terms of causes (energy, industry, transport), the measurement of air pollution itself, or impacts such as damages to ecosystems and health.

Regarding climate-related changes, although it is not an unprecedented topic since more than 50 years ago the role of gases such as CO₂ in this process was already under study (Benton 1970), and new implications have been raised as the technology of detection, modeling, and elaboration of forecasts based on the historical profile that has been traced and, especially, given the lack of an adequate and quick response to such effects (Atkinson and Jacquet 2022). Although SDG 13 deals directly with climate change, encompassing five targets, similarly to air pollution, only three other mentions are made on the subject, along with combating poverty (SDG1), eradicating hunger (SDG2), and sustainable cities (SDG11). Such a scenario raises concerns about the non-integration of objectives.

In recent years a concept called One Health (OH) has gained importance. Considered a holistic, transdisciplinary, and multisectoral concept, which encompasses Human Health, Environmental Health, and Animal Health, it is directly connected to

aspects of public health, urbanization, legal framework, ecotoxicology, multifactorial diseases and cultural practices, which in turn have direct influences on the quality of life, human rights and institutional policies of companies and nations, although some of these aspects are often neglected (Destoumieux-Garzón et al. 2018; Ribeiro et al. 2019). Dye (2022) indicated that the OH approach is the most appropriate for achieving the complex and multiple aspirations of the SDGs of the 2030 Agenda, as this approach seeks to anchor health and development, demonstrating that social justice, environmental protection and economic prosperity depend on and contribute to global health.

The OH approach is a very challenging strategy in developing countries like Brazil, especially to avoid setting goals that are too narrow or too broad, which lack prioritization of needs (Dye 2022). According to Espeschit et al. (2021) Brazil already has the necessary instruments to carry out interventions in the OH approach, but professional alienation, lack of financial resources, and lack of recognition of the intersection of human, animal, and environmental health remain obstacles to its articulation. Aiming to evaluate congruence points for different regions of the world, Laumann et al. (2022), grouped 181 countries into 35 groups based on their regional and economic affinities and found that SDG 17 (partnerships) had the highest number of mentions in connection with tackling climate change, prevailing on all continents except Oceania. Those authors also declared that fundamental variables such as air pollution and disorderly urbanization, with the growth of slums, were directly linked to the increase in global temperature and its consequences.

In addition, it is important to report that the complexity of the indicators, with just under eight years to go before the agreements should be put into effect, is still a hindrance in the process of putting initiatives into operation. Silveira et al. (2021) developed a survey involving five prestigious institutions: the Global Burden of Disease Study (GBD), the Pan American Health Organization, the Sustainable Development Solutions Network, the World Bank and the World Health Organization (WHO), and analyzed their convergences and divergences regarding the health-related SDG indicators. Of the 104 indicators listed by these 5 institutions, only 60 of them were consistent with official Inter-agency and Expert Group SDG indicators. Besides that, out of these 60 indicators, only 22 are included in the lists of the five institutions. This perception demonstrates that there are significant inconsistencies, which certainly delay obtaining decisive information both for decision-making and for monitoring by governance and society of potential advances or setbacks in goals. And, considering the context presented in the OH approach, these

variations make the process of integration and interdisciplinarity work, which seem to be the most suitable for carrying out the SDGs, more difficult (Queenan et al. 2017).

In Brazil, the prospects are huge. Brazil occupies prominence in the international scenario due to its large territory of continental dimensions, high population, and leading role in the production of various goods and commodities. Despite that, Brazil is still a very heterogeneous country in terms of economic development and key environmental variables in its regions (Swart and Brinckmann 2019). Considering that, previous studies demonstrate major weaknesses that signal the non-achievement of targets within the stipulated period. Reports from different surveys indicate that: More than 50,000 people die in Brazil annually due to air pollution (Custódio et al. 2022); Management of decisions related to climate changes impacts and solutions still belong to few groups which control both the production of knowledge and the responses given in crisis events (Lemos et al. 2020); Brazilian cities and their managers are more interested in positioning themselves as smart and technological cities than as sustainable cities (Machado Junior et al. 2018) and that, according to a group of 884 experts, Brazil's chances of completing some of the 17 SDGs is low, and the prioritization of SDG 4 (Quality Education) and SDG 1 (End Poverty) are mandatory tasks to achieve goals aimed at improving health and quality of life (Moreira et al. 2019), since several basic principles shared by health promotion and sustainable development, such as equity, intersectoral methods, and sustainability, help to optimize their influence across traditional sectoral lines.

Considering the established scenario, the 2030 Agenda is an important tool in the search for sustainable and integral development, but the variety of its approaches makes the use of its indicators complex. Therefore, in this work we selected several bibliographies in order to draw attention to issues concerning air pollution and climate change, based on the way in which these themes are covered by the SDGs, adapted to the Brazilian scenario. For this, there is a division into three main sections: the first presents aspects related to air pollution, including the course and status of local public policies established for its evaluation, as well as studies concerning the theme and its already proved consequences, including first some insights from Latin America and then, Brazil. In the second, a similar approach is given to climate change, building its parallel in relation to air pollution. The third section presents a table assembled with data about the current state of SDGs in Brazil, as well as discussing hotspots of action and perspectives for them. This discussion is intended, then, as a subsidy to foster reflections and raise

awareness on the interconnections between human and environmental health in order to better address the gaps that are still found in sustainable development actions.

Air pollution

Chronology and legal aspects

The first studies addressing air pollution in Latin America date back to the 1950s, when universities and bodies linked to the Ministries of Health in various regions began measuring air pollutants, and the establishment of the Pan American Network for Standardized Sampling of Air Contamination – REDPANAIRE, in 1967 was a milestone in this process, as seven years later, monitoring stations would be installed in 14 countries and would later be incorporated into the Global Air Quality Monitoring Program – UNEP/WHO (Colman Lerner et al. 2018). Comparatively, in the study developed by Gómez-Peláez et al. (2020) in cities in South America, although seven decades have passed since the beginning of these actions in the region, more than 100 million people are still directly exposed to increased levels of air pollution, and even though in the period 2010 to 2017 some cities such as São Paulo and Bogotá have registered a decrease in the levels of pollutants such as PM_{2.5}, this is definitely not a regional trend, with continuous surpassing of the rates recommended both by local agencies and bodies and by the WHO itself.

The Brazilian scenario was not less complex. Duarte (2015) brings a very important historical account when describing the attitudes of the then Minister of Planning, João Paulo dos Reis Velloso, who in January 1972 showed a position clearly contrary to any environmental concern through his speeches that considered that the greater pollution in Brazil was actually poverty and that there were still many areas to be polluted, signaling the interest in receiving foreign capital from already developed countries, such as Japan, which sought to continue expanding their productive networks, but found themselves legally limited due to environmental impacts already provoked in their own territories.

There was, at that moment, a great dilemma between the governmental interests in the period of Military Dictatorship in Brazil (1964-1985), which aimed for a format of progress and development at any cost (in a supposed attempt to promote jobs and improve income and life quality of the population), and those of the population itself, which

suffered from the unbridled increase in environmental pollution, especially atmospheric, since the smoke from factories was considered a synonym of success (Duarte 2015). Although in a very inconsistent way, in 1967, Decree-Law 3030/1967 was enacted, which can be established as a founding framework for environmental concerns in Brazil, following trends and strong national and international media pressures, which would later legislate so that any substance that was emitted into the atmosphere could not leave it polluted. Given the lack of means to comply with this decree, it would be revoked shortly afterwards by the National Sanitation Policy, still in force, established by Law 5318/1967 (Arantes 2018).

With direct relation to air quality, it was only between the 1980s and 1990s that Brazil developed clear devices for the quantification of pollutants through the creation of the National Environmental Council – CONAMA (article 6 of the National Environmental Policy of Law 6938/1981) later converted into a consultative and deliberative body by Law 8028/1990, and assumed the role of elaborating norms and criteria for environmental quality standards in the country, through inspection resources (Valadão et al. 2022). CONAMA established in 1989 the National Air Quality Control Program – PRONAR, with the purpose of setting emission limits by sources of pollutants in order to ensure that socioeconomic development was possible, however, in an environmentally safe way. Resolution no. 03, of 1990, defined the levels of national air quality standards (National Air Quality Standards - NAQS), bringing an important contribution to the process of evaluation and control of pollution levels, but due to population, industrial and vehicular growth rapidly became outdated, and only in 2018 Brazil adjusted its concentrations to the standards established by the WHO back in 2005, showing an important delay in comprising the goals (Siciliano et al. 2020).

Scientific evidences

Along this path, scientific production has directly collaborated to prove the real impacts of air quality on the health of populations. In recent years, with increasing awareness of the scarcity of resources and the irreversible impacts of anthropogenic action, some studies can be listed that support the need for immediate actions to help mitigate these processes.

Latin America and Brazil: human exposure to air pollution

Starting with an overview of the American continent and especially Latin America and the Caribbean countries, Korc and Hauchman (2021) made an important warning about the large number of people in several countries, such as the Dominican Republic, Paraguay, Venezuela, Haiti, and Belize, that do not have clean primary sources to cook in their homes, needing to resort to the use of wood and charcoal and producing high levels of pollution, in the middle of 2018. These authors also showed that among the 35 American countries studied, only Canada and the United States had no annual records of PM_{2.5} concentration above WHO recommendations in 2016, a very worrying scenario. At the same time, another study carried out with PM_{2.5} levels in 366 Latin American cities with more than 100,000 inhabitants using satellite data showed that 58% of the population under study (more than 170 million people) live in areas with exposure to air pollution levels above the WHO averages, this increase is directly linked to cities with higher GDP, higher motorization rates, traffic jams, and larger size and inversely proportional to the presence of green areas in the municipalities (Gouveia et al. 2021). Husaini et al. (2022) also demonstrated that Latin America and Caribbean countries still lack studies to explore the regional impacts of air pollution in order to sensitize public gestors and reduce health impacts.

In Brazilian territory, a crucial issue is related to changes in land use, since several agricultural and extractive practices occur without any concern for sustainability. In a broad study involving all 26 Brazilian states and the Federal District in a 20-year historical series (1995 – 2014) to estimate the different types of territorial changes arising from crops, pastures, and forestry and crossing these data with the associated CO₂ emissions, it was noticed that both the highest emissions occurred in the surroundings of the Amazon Biome, as well as the productive models of territorial use that expanded the most in the region, are the ones that most contribute to this type of pollution (generation of greenhouse gases) (Novaes et al. 2017). These data are in agreement with a literature review developed by Urrutia-Pereira et al. (2021) who sought to establish the relationship between exposure to smoke caused by the burning of biomass in the Brazilian Amazon Forest and the implications for human health faced by the population of the surrounding region. Working with a list of publications between the years 2005 and 2021, these authors demonstrated that despite great dissemination in the media, few studies were dedicated to evaluating this theme in the mentioned region, pointing to the urgent need

for actions that provide an improvement in the behavior of the exposed population both in terms of preventing fires and in protective measures to reduce health damage.

Air pollution sources

In Latin America, the rapid increase in urbanization and the emergence of megacities contributed drastically to the accumulation of various pollutants in the atmosphere, especially those produced from the activities of industrial complexes and vehicle fleets (La Colla et al. 2021). As the region is mainly formed by developing countries, the mechanisms for monitoring the sources of pollution are often deficient or absent, contributing to poor air quality management (Riojas-Rodríguez et al. 2016) and, in addition, the accelerated population increase contributes to more anthropogenic polluting activities.

In Brazil, as an extension, wildfires also play a very important role in the generation of pollutants that directly affect the health of populations. Caumo et al. (2022) collected evidence from 27 papers published between 2000 and 2021 to conclude that the most vulnerable populations always present exacerbated clinical conditions (cardiorespiratory, mainly) in episodes immediately before, during, and after fires due to an increase of pollutants, such as particulate matter, which directly agrees with the findings of Ye et al. (2021), albeit in a more restricted period (2000-2015).

Sousa et al. (2020) went even further, exposing that in addition to the Western Amazon region, the territories that extend between the north of the state of Mato Grosso and the southeast of the state of Pará, called “Arco do Desmatamento”, and also Pantanal, in addition to being constantly ravaged by fire, rising temperatures and intense droughts, also have populations exposed to low and lacking hospital infrastructure, especially highly complex ones, not being able to provide effective and fast care. This condition may be associated with what was found in the investigation by Nawaz and Henze (2020) who highlighted that the burning of biomass that has been occurring mainly in the Amazon region, emitting aerosols with large amounts of particulate matter that spreads throughout the Brazilian territory, often causes illness and increase in premature deaths in areas far from the main fires, as reinforced by the study by Bainy et al. (2021).

Health impacts and costs

Floss and Barros (2021) used the report produced by the Lancet Countdown for the year 2019 to prepare a policy brief on key points that should be developed in Brazil in order to address recommendations no. 2, 3, and 4, of the report that deal with: suppressing energy production from burning coal, reducing illegal deforestation to zero by 2030 (as well as carrying out reforestation practices and reducing the burning of biomass) and developing a personalized Brazilian version of air quality index, with online messages that alert the population to the increased risk of pollutants in certain scenarios, respectively. This last recommendation also comes with a direct mention of reducing the burden of diseases related to air pollution, especially in the most vulnerable populations, attesting to the imminent need for clear initiatives in this regard. An example of this is the study by Carneiro, Vila and Vieira (2021) who worked with secondary data from SUS regarding outpatient care for respiratory diseases in children under five years of age in Brazil and observed that most pathologies have stationary or ascending rates, and only asthma cases decreased. In addition, that same study showed rising disease rates in the Southeast region of Brazil, while in the others the levels tended to a stationary state.

Lima et al. (2021), in their turn, when analyzing numbers of hospitalizations for respiratory diseases between 1998 and 2020 in the city of Manaus – AM and the data on atmospheric pollutants obtained in the same period, denoted a strong correlation between them, in addition to obtaining an annual calculation average of more than BRL 19,000.00 (approximately US\$3,900.00 in May/2022 quotation) per hospitalization by the Brazilian Unified Health System (SUS), evidencing a high cost per patient admitted.

The Southeast region, individually, also contributes in a very significant way to pollution, although in a different way from the Amazon axis, and for this reason, it has been the most widely studied over the years, in the verified health impacts, the quality of the monitoring data provided and the pollution control programs implemented. An important study in the city of São Paulo focused on the impacts of air pollution showed that the increase in the atmospheric concentration of particulate matter was highly correlated with the increase in hospitalizations for respiratory diseases in the period from 2008 to 2017, with 302,000 hospitalizations representing a health cost of 111 million dollars (Santana et al. 2020). These results are in line with the research by Abe and Miraglia (2016), who evaluated São Paulo city air pollution using the Health Impact Assessment approach, and pointed out that if São Paulo reached the levels of PM_{2.5} recommended by the WHO (10 μm^3 , at that time) more than 5000 thousand premature deaths would be avoided, as well as guaranteed savings of more than 15 billion dollars.

Gouveia et al. (2017) investigated the same outcomes in the metropolitan region of São Paulo (including 10 municipalities in the state). These authors also observed a correlation between the levels of pollution found and hospitalizations, in this specific case, correlating PM₁₀ levels with cardiovascular involvement. This perspective was also reinforced by Pamplona et al. (2020), who correlated air pollution in the city of São Paulo with congestive heart failure. The recent study by Leirião et al. (2022) also showed that the levels of pollution found in São Paulo probably contributed to the increase in deaths due to the COVID-19 pandemic, emphasizing that reducing pollution levels is also essential from the perspective of coping and improving the chances of death survival in future respiratory disease pandemics.

Other noteworthy studies in the city/state of São Paulo were: Bravo et al. (2016) who, in addition to relating hospital deaths to air pollution, also observed that the cardiovascular effects of PM₁₀ were more significant in population groups with less schooling (indicating the “non-democratization” of pollution); Pérez-Martínez et al. (2017) who observed that policies related to transport/traffic can have a significant impact on reducing pollutants based on their study on the restriction of heavy diesel vehicles; Nakada et al. (2020), Rudke et al. (2021) and Cirqueira et al. (2022) who studied the effects of the COVID-19 pandemic (lockdowns and mobility restrictions) on pollution levels and noticed very heterogeneous results, concluding that the economic, health and vehicular traffic particularities of each city or region in the state of São Paulo should be taken into account in the search for emission mitigation strategies.

Mitigation strategies perceptions and challenges

Another major review developed by Andrade et al. (2017) used studies involving ozone (O₃) emissions and the Metropolitan region of São Paulo - SP, over three decades (1980s-2010s), and demonstrated that challenges still remain for the Companhia de Tecnologia de Saneamento Ambiental (CETESB, Environmental Protection Agency) to the control of pollutants of secondary origin such as O₃ and particulate matter, especially by vehicular sources and emissions. This finding is quite concerning since the state of São Paulo has the best service for monitoring and mitigating atmospheric pollution in Brazil. Studies also show frustrated alternatives that have already tried to reduce the emission of vehicular pollutants in the region, such as the one by Araujo and Araujo (2020) who analyzed the impact of the Vehicle Inspection Program on public health in the city of São

Paulo. This measurement, instituted with the use of public funds, was in force between January 2010 and January 2014, with the purpose of minimizing the emission of pollutants by vehicles registered in the municipality, even so, neither its introduction nor its interruption had any correlation with the decrease in pollutant concentrations and, consequently, with lower rates of health outcomes (hospitalizations and deaths from various pathologies such as infarction, stroke, chronic obstructive pulmonary disease, and neoplasms), which attests to its null influence. Sá et al. (2017), however, points out that actions to change the direction of development towards more sustainable alternatives are still welcome. Regarding the absence of evidence from the Vehicle Inspection Program, Sá et al. (2017) mentioned that more in-depth evaluations are needed to solidify this hasty perception, and that there is no consistent data to attest to the lack of correlation in low- and middle-income regions, reinforcing that these particularities could completely change the results found. This counterpoint demonstrates the need for new assessments on the subject for proper decision-making.

Similar to what occurs in the Amazon region, Santana et al. (2020) verified the correlation between the emission of atmospheric pollutants in São Paulo and the increase in costs and hospitalizations for respiratory diseases between the years 2008 and 2017, realizing that the particulate matter increased year by year in the evaluated period and was highly correlated to the hospitalization rates and the increase in costs, which went from a total of US\$ 111 million for 302 thousand hospitalizations. What is evident is the need for more rigid alternatives to recover from this scenario that has been generalized. Cubatão – SP, a notorious city for having already been considered by the UN as the one with the most polluted atmosphere in the world, in a recent study (Sarra and Mülfarth 2021) that evaluated the historical series 2010-2020, showed, mainly in the years 2015 to 2017, a 62% reduction in the number of exceeding the Air Quality Standard for PM₁₀, which reflected, for example, a 30% drop in the Infant Mortality Rate, a 95% drop in hospitalizations for acute bronchitis and bronchiolitis in children under four years of age and a 60% reduction in deaths of individuals over 60 years of age from diseases of the respiratory system, which allows us to conclude the positive impacts of the recovery and sustainable measures that have been effectively adopted and carried out in this municipality.

The importance of green areas in reducing pollutant levels was also attested by the study by Martins et al. (2021) who, studying tree barks collected in parks in the city of São Paulo, realized that forest fragments help to contain particulate matter and various

heavy metals such as copper and cobalt, even serving as biological monitors that allow tracking of anthropogenic pollution.

Climate change considerations

Brief legal and historical aspects

Similar to concerns about air pollution, attention to climate change, given the great affinity between the topics, has intensified in the last four decades. However, if the scientific demand for solutions to the problems caused by the human action in the environment has instigated several researchers today, it has been part of human knowledge for a long time that we could change the climate. According to Mahony and Endfield (2018), there is a connection that goes back to the period of imperial colonialism perpetrated by European countries, which considered tropical regions, given the variety and abundance of their resources, as inhabited by depraved humans, inferior to the European people. In addition, these authors emphasize that people could already perceive environmental changes, such as deforestation, would alter the rainfall regime, and this became a strategy of domination, even though there was no understanding of atmospheric pollution or global warming.

Following the historical line of important points directly related to the understanding of climate change, as illustrated by Sheehan (2019), in 1824, Fourier described the Earth's natural greenhouse effect and, in 1861, Tyndall proved in the laboratory that water vapor in combination with other gases was capable of producing the greenhouse effect. Later, in 1896, Arrhenius built the first climate model demonstrating the atmospheric influence of carbon dioxide (CO₂), which was confirmed in 1900 when Angstrom established that CO₂ is able to absorb infrared radiation, producing heating, even in slight concentrations. Nevertheless, even with these scientific advances having already been observed in the transition from the 19th to the 20th century, it was only in 1972 that the United Nations held the Stockholm Conference, the first to raise the issue of global warming and seek to establish principles of environmental protection worldwide, that would culminate in events such as Rio 92, the establishment of the Kyoto Protocol and much more recently, in 2016, the Paris Agreement (Sheehan 2019).

Brazil has been identified as a key country when it comes to global climate change (Lahsen and Ribot 2022), but the organization of climate services in the country is

diffused and this seems to be a major national challenge facing the 2030 Agenda (Escada et al. 2021). The country, which has one of the largest emerging economies in the world, is paradoxically a power in terms of biodiversity and the potential for the use of renewable energy sources, and at the same time a major polluter due to forest fires, deforestation, livestock and the use of fossil fuels (La Rovere 2020). Brazil ranks seventh among the countries with the highest emission of greenhouse gases (GHG) and although it has reduced GHGs by 54% between 2005 and 2012, the abandonment of deforestation control policies and the encouragement of predatory agricultural practices will certainly be obstacles to achieving goals directly or indirectly related to climate change (Rochedo et al. 2018).

The consequences of climate change in Brazil and other Latin American countries throughout the 21st century may compromise some important goals of the 2030 Agenda, especially food insecurity; floods and landslides; water shortage; vector-borne disease epidemics; displacement of the Amazon Forest biome; coral bleaching; risks of sea level rise in coastal regions, storms, and erosion, and systemic failure due to cascading impacts of hazards and epidemics (Hagen et al. 2022). The authors of this study also pointed out that the impacts of the risks will be heterogeneous in the region and that the groups most affected will be the populations of rural communities, indigenous peoples, Afro-Latin Americans, women, people with disabilities, and migrants.

Spatially, a study displayed the Brazilian hot-spots sensitive to climate change, based on the Regional Climate Change Index (RCCI) and the Socioclimatic Vulnerability Index (SCVI) (Torres et al. 2012). The first index is directly related to meteorological variables, while the second incorporates regional and social factors, including the availability of water resources and agricultural vulnerability. The RCCI showed climatic hotspots in central Brazil and in the Amazon region. On the other hand, the SCVI revealed the main socio-climatic hotspots in the northeast region (the poorest region in the country) and several hotspots located in the main Brazilian metropolitan regions, such as Manaus, Belo Horizonte, Brasília, Salvador, Rio de Janeiro, and São Paulo.

In addition to the heterogeneity of vulnerability associated with climate change, policies related to its risks, at the level of cities and states, are diffuse and supported by non-governmental stakeholders, organizations of civil society, the private sector, universities, and research institutions. Only 14 of the 27 federative units and 6 cities have climate change policies. The study by Barbi and Ferreira (2017) evaluated these policies based on five main points of analysis: (1) mitigation goals and intentions; (2) adaptation

actions; (3) stakeholder participation; (4) policy implementation; (5) participation in transnational climate change networks. In general, points 1 and 5 are more covered in municipal policies, while points 2, 3, and 4 are better addressed in state policies. The authors also comment that the establishment of climate policies is an important step, but that law enforcement mechanisms are fundamental to ensure that mitigation and adaptation actions are taken.

Returning to the national sphere, two important elements can (and should) be used as a basis for expanding health care in a scenario of a changing climate: Law 12187/2009, which establishes the National Policy on Climate Change (Brazil-NCCP), and the country's national adaptation plan (Brazil-NAP). The Brazil-NAP comprises a general strategy and eleven sectoral strategies, one of which specifically concerns health (Brazil-H-NAP). Still, the absence of explicit references to the right to health shows that the country has considerable room to improve its engagement with the human rights framework, particularly through the establishment of mechanisms to promote transparency, monitoring, and participation of marginalized groups, aiming to increase access and reduce inequalities (Viveros-Uehara 2021).

Impacts of climate change

The increase in average temperature over the last few decades is already well reported in different parts of Brazil (Medeiros et al. 2018; Marengo et al. 2021; Monteiro et al. 2021) and the country has been identified as one of the places with the highest rates of mortality from heat waves attributed to human-induced climate change (Vicedo-Cabrera et al. 2021). A study that evaluated the association between hot waves and hospitalizations in Brazil during the years 2000-2015 showed a higher risk of hospitalizations for hot waves characterized by high daily temperatures and for long durations throughout Brazil, with the exception of the North region (hotter region). After controlling the temperature effect, the association remained for severe heat waves in the south and southeast (cooler regions). Hospitalizations among children aged 0 to 9 years, elderly >70 years, and hospitalizations for perinatal conditions were most strongly associated with hot waves. In a temporal context, the strength of the heat wave-hospitalization association decreased substantially in the south, while an apparent increase was observed in the southeast (Zhao et al. 2019).

Another study conducted in macro-urban areas with data for the years 2000 to 2019 evaluated the association between extreme drought events and mortality and in

general, the data showed an association between drought and general mortality, circulatory mortality, and respiratory mortality. A more robust positive association was found with some population groups, including women and the elderly. There was also great heterogeneity between the areas studied (Salvador et al. 2022). In addition to respiratory and circulatory diseases, studies have detailed the relationship between infectious diseases and changes in the climate, including dengue, malaria, and arboviruses. The increase in temperature and precipitation are the main climatic factors predicting this relationship (Sousa et al. 2018).

After exposing these scenarios, a very strong and important interrelationship between air pollution and temperature rise in Brazil is evident (as in other regions of the world) directly impacting human health, but also jeopardizing the balance of ecosystems, food production, and resource extraction. Discussing such aspects, and seeking to visualize the perspectives of action for making decisions that change this trajectory is fundamental work since one of the trends that have been observed is a Brazilian population remodeling, which will intensify in the future, as an escape from extreme environmental conditions, further exacerbating perceived regional inequalities (Oliveira and Pereda 2020).

Discussion

Table 1 presents the global goals related to the mitigation of impacts directly or indirectly related to air pollution and climate change, adapted for Brazil, and was prepared with information obtained from the website <<https://odsbrasil.gov.br/>>, maintained and updated by the Brazilian Federal Government, in order to allow public monitoring of the goals of the 2030 Agenda.

Of the 23 indicators selected from the six SGDs under study, 13 are in the “elaborated” status (green color status) and only one (Indicator 13.a.1) is not applicable to the Brazilian territory, therefore not having status of completeness. Regarding the indicators with “elaborated” status, both a positive and a negative perception can be traced. On the one hand, as more than half of the indicators selected to discuss the topic of this work already have collected data, this fact allows decision makers, public managers and society as a whole to work on practical strategies to contain damage and achieve better chances of success of the initiatives. Some of them even bring positive perspectives, such as indicator 3.9.2 (although not directly linked to the topics under

discussion) or indicator 13.2.2, which denotes a reduction of more than 1/3 of greenhouse gas emissions (GHG) across Brazil between 1990 and 2016.

On the other hand, there is still a long way to go. For instance, the indicator “Number of deaths, missing persons and persons affected by disaster per 100,000 people”, in a time series from 2015 to 2021, had a national increase of more than 200%. This is certainly cause for concern, as studies show that there is an intimate relationship between air pollution, climate change and natural disasters, whether in Brazil (Marengo et al. 2021; Perez et al. 2020; Matias Ribeiro et al. 2021; Pivello et al. 2021) or in other parts of the world (Chandrappa and Chandra Kulshrestha 2015; Kumar 2021). In addition, indicator 1.5.4, which is complementary to the previous one, demonstrates that less than 40% of Brazilian cities have defined strategies for disaster risk reduction in line with national strategies, denoting that a large part of the national territory is still vulnerable to ongoing environmental impacts and disasters.

It can also be observed that indicators 1.5.2 (SDG 1), 3.9.1 (SDG 3), 11.6.1 (SDG 11), are under construction (the first two being more directly linked to issues of the climate - air pollution axis) which means that sufficient information has not yet been collected in Brazil to define the status of completeness. Of these goals, we cannot understand what condition they are in: whether they have advanced since the agreement made in 2015, or not.

Starting with the first indicator “Direct disaster economic loss in relation to global gross domestic product (GDP)”, the study by Kuhla et al. (2021) points out that the increase in heat stress will cause profound impacts both economically and socially. Through mathematical modeling, the authors point out that productivity at work will fall, favoring price increases and scarcity of resources, severely reducing the purchasing power of individuals, especially in countries such as Brazil, India and Indonesia. Nevertheless, the study by Giannini et al. (2017) evaluated the impacts of climate change on 95 species of pollinators in 13 different types of crops in Brazil, and in the projections (considering the worst scenarios until the end of the 21st century), about 88% of Brazilian municipalities will face loss in the number of pollinating species, which can reach 100% of the species for some crops, such as sunflower. This scenario clearly contributes to the increase in food insecurity, with the municipalities with the lowest GDP being the most affected, putting more than 6 million people at risk.

Table 1

2030 Agenda goals, targets and indicators, and their current status in Brazil

SDG1 - No poverty	
Global Target 1.5	By 2030, build the resilience of the poor and those in vulnerable situations and reduce their exposure and vulnerability to climate-related extreme events and other [...] disasters.
Indicator 1.5.1	Number of deaths, missing persons and persons affected by disaster per 100,000 people.
Indicator 1.5.2	Direct disaster economic loss in relation to global gross domestic product (GDP).
Indicator 1.5.3	Number of countries with national and local disaster risk reduction strategies.
Indicator 1.5.4	Proportion of local governments that adopt and implement local disaster risk reduction strategies in line with national disaster risk reduction strategies.
Brazil	Target was maintained.
Status 2022 - 1.5.1	Elaborated - Data series: 2015-2021 - National ↑ of 209.5%.
Status 2022 - 1.5.2	Under construction.
Status 2022 - 1.5.3	Elaborated - Data series: 2018-2021 - Brazil possesses strategies to manage risks.
Status 2022 - 1.5.4	Elaborated - From its 26 states and the Federal District, Brazil's national average is 38.8% of cities with implemented strategies.
SDG2 - Zero hunger	
Global Target 2.4	By 2030, ensure sustainable food production systems [...], that strengthen capacity for adaptation to climate change, extreme weather [...].
Indicator 2.4.1	Proportion of agricultural area under productive and sustainable agriculture.
Brazil	Target was adapted including the importance of research, technical assistance and rural extension.
Status 2022 - 2.4.1	No data is available.
SDG 3 - Good health and well-being	
Global Target 3.9	By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination.
Indicator 3.9.1	Mortality rate attributed to household and ambient air pollution.
Indicator 3.9.2	Mortality rate attributed to unsafe water, unsafe sanitation and lack of hygiene (exposure to unsafe Water, Sanitation and Hygiene for All (WASH) services).
Indicator 3.9.3	Mortality rate attributed to unintentional poisoning.
Brazil	Target was maintained.
Status 2022 - 3.9.1	Under construction.

Status 2022 - 3.9.2	Elaborated - Data series: 2000-2019 - National ↓ of 32.69%.
Status 2022 - 3.9.3	Elaborated - Data series: 2000-2019 - National ↑ of 21.42%.
SDG 11 - Sustainable cities and communities	
Global Target 11.6	By 2030, reduce the adverse per capita environmental impact of cities (special attention to air quality and waste management).
Indicator 11.6.1	Proportion of urban solid waste regularly collected and with adequate final discharge out of total urban solid waste generated, by cities.
Indicator 11.6.2	Annual mean levels of particulate matter (i.e. PM2.5 and PM10) in cities (population weighted).
Brazil	Target was adapted including the implementation of air quality monitoring systems and solid waste management plans in all cities with +500 thousand inhabitants by 2030.
Status 2022 - 11.6.1	Under construction.
Status 2022 - 11.6.2	No data is available.
Global Target 11.b	By 2020, substantially increase the number of cities and human settlements adopting and implementing integrated policies and plans towards [...] climate change [...].
Indicator 11.b.1	Number of countries that adopt and implement national disaster risk reduction strategies in line with the Sendai Framework for Disaster Risk Reduction 2015–2030.
Indicator 11.b.2	Proportion of local governments that adopt and implement local disaster risk reduction strategies in line with national disaster risk reduction strategies.
Brazil	Target was adapted by changing the deadline to 2030 instead of 2020 and by reducing some points of uncertainty (simplification).
Status 2022 - 11.b.1	Elaborated - Data series: 2015-2021 - Brazil possesses strategies to manage risks.
Status 2022 - 11.b.2	Elaborated - From its 26 states and the Federal District, Brazil's national average is 38.8% of cities with implemented strategies. <i>Same data as 1.5.4.</i>
SDG 12 - Responsible consumption and production	
Global Target 12.4	By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle [...] and significantly reduce their release to air, water and soil [...].
Indicator 12.4.1	Number of parties to international multilateral environmental agreements on hazardous waste, and other chemicals that meet their commitments and obligations [...].
Indicator 12.4.2	(a) Hazardous waste generated per capita; and (b) proportion of hazardous waste treated, by type of treatment.
Brazil	Target was maintained.
Status 2022 - 12.4.1	Elaborated - Data series: 2002-2019 - Brazil has signed international multilateral agreements on hazardous waste and other chemicals.
Status 2022 - 12.4.2	No data is available.
SDG13 - Climate action	

Global Target 13.1	Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries.
Indicator 13.1.1	Number of deaths, missing persons and directly affected persons attributed to disasters per 100,000 population.
Indicator 13.1.2	Number of countries that adopt and implement national disaster risk reduction strategies in line with the Sendai Framework for Disaster Risk Reduction 2015–2030.
Indicator 13.1.3	Proportion of local governments that adopt and implement local disaster risk reduction strategies in line with national disaster risk reduction strategies.
Brazil	Target was slightly adapted by adequating terms to their best equivalents in Brazilian Portuguese
Status 2022 - 13.1.1	Elaborated - Data series: 2015-2021 - National ↑ of 209.5%. <i>Same data as 1.5.1.</i>
Status 2022 - 13.1.2	Elaborated - Data series: 2018-2021 - Brazil possesses strategies to manage risks. <i>Same data as 1.5.3.</i>
Status 2022 - 13.1.3	Elaborated - From its 26 states and the Federal District, Brazil's national average is 38.8% of cities with implemented strategies. <i>Same data as 1.5.4.</i>
Global Target 13.2	Integrate climate change measures into national policies, strategies and planning.
Indicator 13.2.1	Number of countries with nationally determined contributions, long-term strategies, national adaptation plans [...] as reported to [...] the United Nations (UN) Framework Convention on Climate Change.
Indicator 13.2.2	Total greenhouse gas emissions per year.
Brazil	Target was adapted by adding the integration of the specific Brazilian specific "Política Nacional sobre Mudança do Clima (PNMC)" to the strategies.
Status 2022 - 13.2.1	Elaborated - Four National Communications in 2004, 2010, 2016 and 2020.
Status 2022 - 13.2.2	Elaborated - Data series: 1990-2016 - National ↓ of 35.25% in total emissions.
Global Target 13.3	Improve education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction and early warning.
Indicator 13.3.1	Extent to which (i) GCE and (ii) ESD are mainstreamed in (a) national education policies; (b) curricula; (c) teacher education; and (d) student assessment.
Indicator 13.3.2	Number of countries that have communicated the strengthening of institutional, systemic and individual capacity-building to implement [...] actions.
Brazil	Target has become broader than the UN's original, not restricted to global climate mitigation.
Status 2022 - 13.3.1	No data is available.
Status 2022 - 13.3.2	No data is available.
Global Target 13.a	Implement the commitment undertaken by developed-country parties [...] of mobilizing jointly \$100 billion annually by 2020 from all sources to [...] operationalize the Green Climate Fund [...].
Indicator 13.a.1	Amounts provided and mobilized in US dollars per year in relation to the continued existing collective mobilization goal of the \$100 billion commitment through to 2025.

Brazil	Target not applicable to Brazil. This goal is located at an international level and refers to a commitment assumed by developed countries.
Global Target 13.b	Promote mechanisms for [...] effective climate change-related planning and management in least developed countries [...] focusing on women, youth and local and marginalized communities [...].
Indicator 13.b.1	Number of least developed countries [...] with nationally determined contributions, long-term strategies, national adaptation plans [...] as reported to [...] the UN Framework Convention on Climate Change.
Brazil	Target was adapted by adequating terms to their best equivalents in Brazilian Portuguese as well as Brazilian conditions.
Status 2022 - 13.b.1	No data is available.

↑ - Increase

↓ - Decrease

GCE - Global citizenship education

ESD - Education for sustainable development

Climate-changing related target



Air pollution related target



Description of the target condition in Brazil



Indicator not directly linked to the target



Indicator directly linked to the target



Target had no alterations in Brazil



Target had one or more alterations in Brazil



Target is not applicable



Brazil has provided data regarding the indicator



Brazil is still collecting data to fulfill the indicator



Brazil provided no data regarding the indicator



1 – The 2030 Agenda has 17 SDGs, of which six (1, 2, 3, 11, 12, and 13) were selected regarding the theme of the present discussion. Within each SDG there are targets, and each target has its own indicators.

- 2 – This table was structured by first indicating one or more targets within each chosen SDG. For each target, its indicators classified as directly or indirectly linked to the target based on their specificity were listed. Next, the situation of the target in Brazil was displayed, as well as the current status of each of the indicators belonging to each target in 2022.
- 3 – The colors selected for the lines of the SGDs seek to symbolize the same tones chosen by the UN.
- 4 – The colors regarding Brazil's data completion status on indicators of each target represent their level of concern – green: data is available (actions are being taken); yellow: need of attention (the status is still under construction); red: major concerns (there is no information available about the status of the indicator).

This is not an isolated perception. Santos et al. (2022), working with projections of temperature increase and its impacts on agriculture and the economy of different Brazilian regions, also pointed out that climate change has the potential to cause a significant retraction of GDP, and even deepen existing social inequalities, for impacting mainly the poorest families or those directly dependent on agriculture. Leal Filho et al. (2018) and Costa et al. (2019) also demonstrate the climatic factors contributing to financial losses caused by the increase and distribution of vector-borne diseases and accidents with venomous animals (snake bites), respectively.

Actions that contribute to the reduction of atmospheric pollution can, on the other hand, positively affect the climate and quality of life of a population. An example of this was the study Martins et al. (2021), who noted that in BRICS countries (Brazil, Russia, India, China and South Africa), the number of vehicles in use is linearly correlated with GDP progress. For these countries, the adoption of electric cars, for example, is not only a strategy to mitigate environmental impacts, but represents a real possibility for economic growth, as in highly developed nations such as Iceland and the Netherlands, where demand for clean energy grows continuously. And, as also demonstrated by Asere and Blumberga (2020), the level of energy efficiency and quality of a country is directly linked to the progress of its GDP. During the COVID-19 pandemic, ESG (environmental, government and social) measures proved to be of great importance in dealing with the political, social and health crisis. According to Jesus and Nascimento (2021), EMBRAPA Soils (a unit of EMBRAPA – Brazilian Agriculture Research Corporation) as a public company, implemented actions with multiple focus, developing a social, governmental and environmental role, with the provision of online courses, production of educational lives, donation of funds for COVID-19 detection tests and support for the development of public policies on environmental issues. This type of action can easily be adapted to the particularities of companies in the public and private sectors, creating a network of contributions that combine efforts (integrity, diversity, human rights, efficiency, prevention of corruption, natural resources protection) to reach the different SDGs established.

The second indicator “Mortality rate attributed to household and ambient air pollution is a major concern. Rosário Filho et al. (2021) showed that the household use of “dirty” fuels like coal and biomass represents a serious health risk in developing countries, especially because people spend long periods in their homes and more vulnerable groups such as children, end up being the most affected, especially for

respiratory pathologies. Fernandes et al. (2018), in a study with 996 individuals with moderate or severe asthma, exposed to scenarios of smoking, household pollution or the two exposures combined, observed that individuals exposed to household pollution or with double exposure were those who presented the most severe cases of asthma and worsening of general health status. It is noteworthy that the use of rudimentary stoves, the main sources of household pollution related to the burning of “dirty” fuels, is particularly important in rural and less developed regions in Brazil. A study developed with secondary data on the Brazilian population pointed out that few studies have been dedicated to addressing the issue and that more than 30 million people still use firewood for cooking, especially due to the high price of liquefied petroleum gas (LPG), aggravating its risks of illness in the short and long term (Gioda et al. 2019).

The last indicator under construction is “Proportion of urban solid waste regularly collected and with adequate final discharge out of total urban solid waste generated, by cities”. Despite this information gap, investigations already carried out show that Brazil still faces major problems in the collection and especially in the final disposal of waste, and according to Alfaia et al. (2017) less than 60% of the collected waste has an adequate destination in Brazilian municipalities and, especially in small municipalities, there are important difficulties in adapting to the Brazilian National Policy on Solid Waste (NPSW) (Pereira and Fernandino 2019). Morita et al. (2021) in their review on the subject in Brazil, drew attention to the fact that inadequate management of solid waste is directly linked to the contamination of all environmental compartments (especially soil and water) and that, on a national scale, many of these impacts have gone unnoticed. The need for more efficient alternatives both from a legal and political framework, as well as sustainable technologies, is urgent for those authors.

In an even more complex sphere are indicators 2.4.1 (SDG2), 11.6.2 (SDG 11), 12.4.2 (SDG 12), 13.3.1, 13.3.2 and 13.b.1 (SDG 13), displayed on Table 1, for which no information is available. Given the importance of these indicators for a better understanding of the dimension in which the two problems listed are faced, an important temporal gap in data on the part of Brazilian governments is evident, as well as the difficulty encountered by different social sectors in monitoring the work that needs to be done to achieve the goals. Indicator 2.4.1 raises an extremely complex issue to be addressed in Brazil, which is the expansion of its agricultural frontiers in a sustainable way. There is great lobbying both by sectors that ignore the pressures caused by agribusiness on ecosystems, as well as by initiatives that establish a conflict between

small producers, large-scale producers, universities, and research centers, instead of realizing that everyone efforts should be on the same side of the discussion (Lahsen et al. 2020). Guida et al. (2018) demonstrated that pesticides currently used in Brazil for the cultivation of different plants are capable of contaminating the atmosphere, even in more distant regions such as mountains, whereas Sun et al. (2019) pointed out that increasing pollution will eventually self-limit the growth of crops, since the temperature increase triggered (in a model of 1.5°C to 2°C) by the end of the 21st century will affect more than 95% of countries, with India and Brazil being the first two in the ranking.

As for indicators 11.6.2 and 12.4.2, the first stands out in this discussion because it is directly related to the quantification of particulate matter, in the case PM₁₀ and PM_{2.5}, in relation to the annual averages by the population size of Brazilian cities. Certainly, the study developed by Vormittag et al. (2021) reflects the great lack of coverage in Brazilian territory of services for monitoring and evaluating air quality in real time and with easy access and understanding by health managers and the population in general. This non-monitoring is a chronic problem, caused by the disorganization of responsibility between the public sector as to who is responsible for the process, and regions such as the Amazon and Cerrado, often subject to forest fires and heat waves, do not have this adequate follow-up (Silva and Vieira 2017). The indicators related to SDG13, on the other hand, are mainly about the need to improve policies, initiatives to prevent climate change and the introduction of environmental education content in the training of teachers, students and in the construction of national curriculum matrices. The absence of data in this sense corroborates the view presented by Frizzo and Carvalho (2018) who emphasized that environmental education in Brazil is silenced, extremely summarized (in the context of the National Education Plan and the National Common Curricular Base) to mentions about concepts of the global environmental discourse, in an extremely general approach and alien to the local reality. De Simoni et al. (2021) in their dossier on air quality in Brazil, reiterate that the country is the largest emitter of O₃ precursor gases in Latin America and, therefore, has an extremely relevant role in the emission of short-lived climate pollutants, directly related to the process of global warming. This group of authors also emphasizes that, although Brazil has a certain political framework for the introduction of more restrictive measures to guarantee air quality, the lack of a timetable and legal certainty in the application of sanctions to deviations does not provide effectiveness of actions.

Regarding the advancement of public policies in relation to environmental health, Brazil has not shown conclusive steps for some years. Silva et al. (2019) draw attention to the fact that recently, although many of the problems identified in Brazil are still reversible, Brazilian environmental policy has been going backward in its achievements, including an increase in flexibility for Brazilian and international companies in the face of issues on which no more space or time could be wasted. The urban-rural-industrial axis has complex characteristics, in which highly polluting activities do not receive specific inspection and legal punishment. If, on the one hand, the increased space in public policies for the discussion of environmental risk from the perspective of the SUS represents an important advance in the last three decades, there is still a difficulty in identifying and solving issues worldwide, that actually start on a community/local scale. Government positions, especially since 2016, represent steps backward in several areas of environmental health (Freitas et al. 2018), which need collaborative, multidisciplinary, and political-economic work to be overcome (Pettan-Brewer et al. 2021). According to the document presented by the Organization for Economic Co-operation and Development – OECD (2021), the need to eliminate gaps in responsibility between institutions and government parties is critical so that Brazil can consolidate its development without completely compromising its biodiversity and the health of its population.

Therefore, it can be said that the empty spaces detected in this survey are extremely important for the advancement of the Brazilian sustainability program and the absence of this information places Brazil in a delicate situation. These gaps, often associated with political disinterest, make many research and technology initiatives find a path of infra-legality (Hochstetler 2021) to develop their work, turning them fruitless, even though authors such as Mesquita and Bursztyn (2016) have already denounced that the weak interaction between sectors, favors the advancement of environmental changes that widen social inequality and increase vulnerability and the risk of poverty. The alert proposed by this discussion is added to existing initiatives that wish to emphasize the urgency of improving the air quality of the Brazilian population, not only because of its influence on a global scale, but also because of its fundamental connection to the difficulty of achieving sustainable progress, financially and ecologically.

Concluding remarks

Given the above, some conclusions can be drawn. Firstly, the variety of topics covered by the 2030 Agenda represent a challenge for developing countries, such as Brazil, in which several actions still need to be taken on in their practical aspects. Secondly, the development of research that delve into multidisciplinary alternatives to address the challenges already identified is crucial. In this sense, broad social sectors are called upon to contribute to the achievement of better panoramas in several of the indicators presented in this discussion. The numerous regional differences that make these initiatives difficult can find in environmental education an important ally in the training of well-prepared personnel with a realistic view of particular problems and how to circumvent them in order to achieve a model of sustainable development. The planning of new research and government decision-making must be parallel and convergent processes, which consider the need to prevent and reduce risks to health and the environment and give priority to alternatives that minimize the socioeconomic inequalities that are still so marked in the Brazilian territory.

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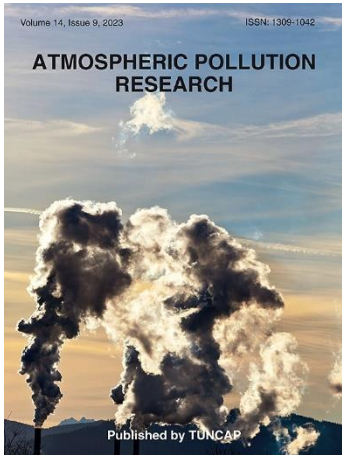
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6.2 Manuscrito II

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In the line of fire: Analyzing burning impacts on air pollution and air quality in an Amazonian city, Brazil

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Abstract

Brazil is grappling with escalating wildfire incidents, particularly in the ecotone region of Cerrado-Amazon, attributed to climate change and anthropogenic factors. These wildfires significantly impact air quality, posing health and environmental risks to the population. This study aimed to assess the influence of wildfires on air quality in Sinop, a city located in Northern Mato Grosso, Brazil. The primary focus was on understanding the behavior of air pollutants during and after wildfire events. Air quality data were obtained from modeling dataset, while meteorological data from ground-based monitoring, and wildfire data from the National Institute of Spatial Research of Brazil. Statistical analyses were employed to investigate pollutant variations and their relationships with meteorological parameters and wildfire intensity indicators. The study revealed a significant impact of wildfires on pollutant concentrations, with ozone levels rising immediately after fires and remaining elevated for several days. The particulate matter (PM_{2.5} and PM₁₀) concentrations increased a few days after fire events. Fire radiative power (FRP) correlated with O₃ levels, suggesting it is an intensity indicator. Temperature exhibited a consistent positive correlation with all pollutants, highlighting its role in pollutant dynamics. During wildfire events, there was a notable increase in days with poor air quality classifications, particularly for O₃. The findings underscore the multifaceted relationship between wildfires, meteorological conditions, and pollutant concentrations pointing to the importance of holistic air quality management strategies in fire-prone regions. Such studies are crucial for guiding environmental policies, safeguarding public health, and advancing scientific understanding in the face of escalating wildfire challenges.

Keywords: Amazon, Agribusiness, Emissions, Public Health, Wildfires.

1. Introduction

Brazil holds a prominent position in terms of wildfires, both in South America and globally, ranking third among countries with the highest occurrence of wildfire hotspots in the last decade (Targino et al., 2024). This perception is concerning, especially because of the increasing frequency of large fires (Cobelo et al., 2023) and their close relationship with climate change and its consequences (Mansoor et al., 2022). In recent years, such as 2019 and 2020, Brazilian biomes have garnered international attention due to the unprecedented frequency and magnitude of fire events (Pivello et al., 2021).

The Cerrado-Amazon ecotone is one of the most vulnerable areas to anthropogenic actions in Brazil. Situated amid the territorial strip known as the "Arc of Deforestation," this transitional area between the Amazon and the Cerrado (the two largest Brazilian biomes) covers nearly 5% of the national territory (Reis et al., 2021) and encompasses the states of Pará, Maranhão, Tocantins, Rondônia, and Mato Grosso (Maciel et al., 2016). Considered one of the world's largest agricultural frontiers, this region of rich biodiversity has become severely susceptible to fragmentation and environmental pollution, posing risks to local populations and native species (Marques et al., 2019).

The state of Mato Grosso (MT) can be lighted in comparison to the others, since more than 60% of its economic activities are linked to the agricultural sector, as pointed out by the Mato Grosso Institute of Agricultural Economics (IMEA, 2023). Temporal and spatial changes associated with agricultural activities, which often include the process of deforestation, contribute to the occurrence of episodes of anthropogenic biomass burning (Pereira et al., 2011; Wu et al., 2023). Sinop is one of the municipalities in the north of the state that plays a leading role in grain production (Wesz Junior, 2022), and was established under Brazil's Plan for National Integration (PIN) for the occupation of the Legal Amazon in the 1970s, with a population of approximately 200,000 inhabitants (IBGE, 2023).

Early in the last decade, Silvestrini et al. (2011) mentioned that fire risk in Brazil could be more directly influenced by climatic factors than by anthropogenically caused fires since favorable weather conditions are a prerequisite for human-caused wildfires.

However, recent studies show that, although fires have natural causes, they are now much more strongly linked to anthropogenic activities, with climate change as a background inextricably associated with and modified by these actions (Pivello et al., 2021; Diele Viegas et al., 2022). The study by Brando et al. (2020) projected that due to climate changes, the area burned by wildfires in Amazon will double by 2050, affecting 16% of the biome area.

Scientific evidence also shows that precipitation is decreasing in the southern Amazon region, leading to more dry days (Dubreuil et al., 2017; Leite-Filho et al., 2021). Le Roux et al. (2022) point to a potential vicious circle in which increased fires triggered by prolonged droughts increase vulnerability to new fires, especially in degraded Amazon and Cerrado areas. Shi and Touge (2022) emphasize that most fires in Mato Grosso occur in illegally deforested areas, which contributes to increased fire risk. The complex dynamics of deforestation, despite initiatives such as the soy moratorium, underscore the multifaceted nature of fire risk in Brazil (Kuschnig et al., 2021).

Wildfires are also directly linked to air pollution and low air quality (Sánchez-Balseca and Pérez-Foguet, 2020; Requia et al., 2021a; Scott, 2023). Some of the main pollutants from biomass burning, such as black carbon, particulate matter (PM_{2.5} and PM₁₀), and volatile organic compounds (VOCs) (O'Dell et al., 2020), have the potential to contaminate water bodies. The United Nations Environment Programme (UNEP) asserts that these substances can cause landslides, contribute to global temperature rise, compromise carbon recycling, pose a threat to a wide variety of species, and induce the emergence of storms and electrical discharges that can ignite new fires (UNEP, 2022).

The effects of particulate matter on the reduction of air quality and illness have already been highlighted in Brazil by previous studies (Mataveli et al., 2019; Ye et al., 2021). Tropospheric ozone can also be produced by fires, but indirectly (Lei et al., 2021). The presence of VOCs and nitrogen oxides (NO_x [= NO + NO₂]) during wildfires in combination with sunlight triggers photochemical processes that contribute to the increase in ozone levels (Kanchana et al., 2020). The increase in O₃ concentration itself can also damage vegetation by reducing stomatal conductance and thus dry deposition. The feedback resulting from these reactions is the enhancement of O₃ levels (Lei et al., 2021). However, these processes can be influenced by various factors such as the local temperature and the age of the plume (Jaffe and Widger, 2012; McClure and Jaffe, 2018).

In this sense, the link between wildfires and the air pollution they generate has been well-established around the world (Vicente et al., 2011; Garcia-Hurtado et al., 2014;

Golobokova et al., 2020; Artés et al., 2022; Schneider and Abbatt, 2022). The investigation of deviations in air quality after fire events has attracted the attention of several research groups, whose results indicate, among other things, an increase in hospitalizations, changes in learning, circulatory disease, and premature births as their consequences (Nunes et al., 2013; Reddington et al., 2015; Machado-Silva et al., 2020; Butt et al., 2021; Requia et al., 2021b). At the same time, the poor understanding of prescribed fires, which excludes traditional practices, leads to the accumulation of combustible material, which favors new fires (Hiers et al., 2020). This may limit future urban and agricultural expansion due to resource depletion and climatic changes themselves (Moura and Da Silva Júnior, 2023). Wildfires have far-reaching consequences as pollution spreads thousands of miles from the source (by entering the air column and being transported by the wind) according to the United States Environmental Protection Agency and other authors (Bolaño-Díaz et al., 2022; Brum et al., 2023; Prist et al., 2023; USEPA, 2023). Wu et al. (2023) found that about 0.7% of all deaths and 0.5% of hospitalizations are due to particulate matter generated by wildfires. A recent study by Coker et al. (2022), indicated that with every $10 \mu\text{g m}^{-3}$ increase in $\text{PM}_{2.5}$, respiratory hospitalizations increased by more than 5%, occurring two to three days after wildfires.

Particularly vulnerable groups such as pregnant women, people with pre-existing conditions, children and the elderly are at increased risk, leading to premature deaths and significant economic losses (Reid et al., 2019; Marlier et al., 2020; Ye et al., 2022; Cobelo et al., 2023; Scott, 2023). To make matters worse, inadequate air quality monitoring in most of the Brazilian territory makes it difficult to accurately assess the exposure of the population, which is a greater challenge in other countries of the Global South (De Moura and Da Silva Junior, 2023).

While Sinop-MT was previously recognized as a major timber center (Nascimento et al., 2019), it has now become an exemplary "agribusiness city" due to the expansion of the production of commodities such as soybeans and maize (Coy et al., 2020), which is associated with significant land use changes and climate impacts (Mello-Théry et al., 2020; Sabino et al., 2020). Although previous studies have pointed to the role of drought as a factor influencing the occurrence of fires in Mato Grosso (Rossi and Santos, 2020), the complex relationship between forest fires and the dynamics of air pollutants has not been assessed. This lack of data makes it impossible to analyze how fires affect the regional atmosphere and represents the knowledge gap under investigation.

Brazil is currently experiencing a fierce conflict between the environmental perspective and land ownership (Shinde et al., 2022). Although progress towards sustainability is evident among decision-makers and stakeholders, for many producers in the Cerrado-Amazon transition zone, environmental issues are primarily analyzed in terms of financial gains or losses before being considered in terms of social impacts or the need for alternatives that enable economic development without harming ecosystems (Mello-Théry et al., 2020).

Considering this scenario, the study of wildfire events in the north of Mato Grosso fulfills the need for research that helps understand the mobilization of pollutants and their sources in small and medium-sized cities (Da Silva Júnior et al., 2023). Therefore, the present study aims to assess the mobilization of air pollutants over a year in Sinop - MT, particularly after forest fire events, to gain a better understanding of their behavior and promote preventive measures that minimize the impact of such events on human health.

2. Material and methods

2.1 Study area

This study was conducted in the city of Sinop (11°50'53" S, 55°38'57" W), located in the north of Mato Grosso State, approximately 500 km from the state capital, Cuiabá (Sinop, 2023) (Fig. 1). The municipality has an area of 3,990.87 km², of which about 70 km² are urbanized, with a population density of 49.13 inhabitants/km² (IBGE, 2023). According to the Köppen-Geiger classification, the city has a Tropical savanna climate (Aw). It receives an average annual precipitation of over 1900 mm, has an average annual temperature of 24.7 °C, and experiences a very intense and hot dry season between May and September each year, as most cities in the state, and earlier than Acre and Rondonia, for example (Khand et al., 2017; Volpato et al., 2022). Vegetation characteristic of the transition between the Amazon and Cerrado prevails in the region (Biudes et al., 2022). The area is highly modified (changes in land cover) due to the expansion of livestock and grains cultivation, as well as the distribution of land as a result of land reform (Casavecchia et al., 2019), and is frequently affected by fires. Rossi and Santos (2020) found that in the driest years, burned areas in the region are proportionally larger.

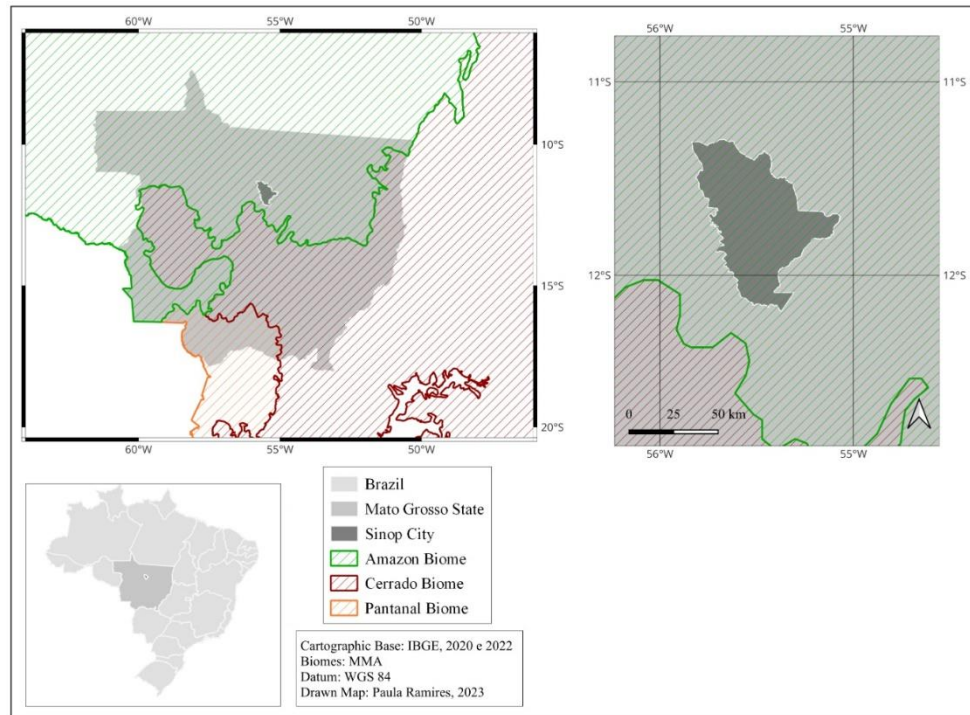


Fig. 1. Map showing the biomes found in Mato Grosso and the geographic location of Sinop.

2.2 Air quality data

The O_3 (ozone), $PM_{2.5}$ (fine particulate matter), and PM_{10} (coarse particulate matter) levels (all expressed in $\mu g\ m^{-3}$) were derived from the modeling dataset sourced from the European Center for Medium-Range Weather Forecasts (ECMWF), specifically, the Copernicus Atmosphere Monitoring Service (CAMS), which provides daily analyses and forecasts including reactive trace gases, greenhouse gases, and aerosol concentrations (Gardin and Requia, 2023). Despite being developed for studies on the European continent, Inness et al. (2019) presented the global validation of CAMS for $PM_{2.5}$ using ground observations conducted by AERONET - Aerosol Robotic Network.

Given this, its application in the study of air pollution in Brazil has become popular in recent years. Although no direct validation of CAMS data is available in Brazil due to the lack of air quality monitoring in several regions of the country, other Brazilian researchers have used the same tool with consistent data (Carvalho et al., 2022; Castelhana et al., 2022; Oliveira et al., 2023; Requia et al., 2022; Tavella et al., 2022; Tavella et al., 2023). Inness et al. (2019) also emphasized that the CAMS data are quite

suitable for reproducing seasonal and monthly variations in pollutants such as ozone (O₃), carbon monoxide (CO), and nitrogen dioxide (NO₂).

The data was extracted every day at around 12 ± 1 pm, utilizing The Weather Channel application provided by IBM, USA (Leão et al., 2021).

2.3 *Weather data*

The correlation between climatic variables and air pollutants was also investigated in this study. The climatic data, including daily average temperature (°C), wind velocity (m s⁻¹), humidity (%), atmospheric pressure (hPa), UV radiation index, and precipitation (mm), were collected from an automated station situated in Sinop (11°87' S, 55°57' W) at an altitude of 370 meters. These data were obtained from the Agrometeorological Monitoring System (Agritempo), developed by the Brazilian Agricultural Research Corporation (EMBRAPA) in partnership with the Brazilian National Institute of Meteorology (INMET) (Agritempo, 2023), which is a web-based platform offering users online access to weather and agrometeorological information from various municipalities and states across Brazil (Carvalho et al., 2017).

2.4 *Wildfires data*

We collected the wildfire data from the "Queimadas" tool that is maintained by the National Institute of Spatial Research of Brazil—Instituto Nacional de Pesquisas Espaciais - INPE. This data includes the date, latitude, and longitude of each wildfire occurrence (burned pixels) and the number of fire spots (fire foci) identified. Additionally, it supplies the fire radiative power (FRP), a quantifiable gauge of emitted radiant heat. FRP is widely employed to estimate fire intensity, a parameter correlated with the rate of combustion and the emission of smoke. This measurement is expressed in megawatts (MW), as discussed by Vadrevu and Lasko (2018). According to Silva Junior et al. (2018), FRP can be labeled in four intervals: ≤ 50 MW (low intensity), $50 < 500$ MW (moderate to high intensity), $500 \leq 1000$ MW (very high intensity), and > 1000 MW (extreme intensity).

We accounted for all wildfire records in Sinop between January 1st, 2022, and December 31st, 2022. INPE derived wildfire data from seven satellite observations, which are NOAA-18, NOAA-19, METOP-B, MODIS (NASA TERRA and AQUA), VIIRS

(NPP-Suomi and NOAA-20), GOES-16, and MSG-3, as described by Requia et al. (2021a). Table 1 provides a summary of the multisource datasets used in this study.

2.5 Data analyses

We assessed the impact of the fires by calculating the mean $\pm$ standard error of mean (SEM) of the concentrations of the three selected pollutants on days without fire, on days with fire outbreaks, and up to five days after the start of the fire episode, resulting in the following groups: non-wildfire day, day 0 (when a fire episode happened), day 1, day 2, day 3, day 4, and day 5. This 5-day lag was considered following Honscha et al. (2023) and Yang et al., (2020) who observed the lagged effects of meteorological variables on air pollutants up to 5 days. Since there were days when consecutive fires were observed, redundancy occurred in the days considered in each group. We performed the Shapiro-Wilk test to confirm the normality of the data and the Levene test to verify homoscedasticity. One-way analysis of variance (ANOVA) followed by Tukey's was used to compare all categories, for O_3 , and followed to Dunnett's multiple comparison test was applied to compare all the categories to the non-wildfire day for $PM_{2.5}$ and PM_{10} .

Pearson correlation was also performed between the meteorological variables and air pollutants for each of the previously established categories, to investigate the existence of a relationship between parameters directly related to fires – fire radiative power (FRP) and number of fire foci per day – and pollutants (O_3 and $PM_{2.5}$), as it was already applied by other groups (Liu et al., 2020; Beringui et al., 2023; Yousaf et al., 2024). PM_{10} was excluded due to its high redundancy with $PM_{2.5}$. This redundancy seems to be a feature that is not unique to Sinop, as another study observed a similar pattern in Barão de Melgaço, MT (Santos et al., 2016), and could be a consequence of the main sources of particulate matter in the central-western region of Brazil (Santanna et al., 2016), as the $PM_{2.5}/PM_{10}$ ratio in Sinop is also very stable.

In addition, to assess the impact of fire events on the concentration of air pollutants, we divided the daily concentrations of ozone and particulate matter into quartiles (Q1 (lowest), Q2, Q3, and Q4 (highest)) for both days when fires occurred and the days they did not. From this, we calculated the percentage of days (non-wildfire and wildfire) in each of the four quartiles. To analyze whether there was an increase in the number of days in the highest quartiles, the Chi-square test for trend was used. Statistical significance was accepted at $p < 0.05$.

Furthermore, a principal component analysis (PCA) was performed considering meteorological parameters and concentrations of O₃ and PM_{2.5}. For this purpose, the average values of all tested concentrations for each pollutant were evaluated. The analysis was based on the correlation between the variables and the graph created considered the two axes (factors) with the greatest contribution to the analysis.

Concerning the methodology of the Air Quality Index (AQI), it involves creating sub-indices for individual pollutants and subsequently aggregating these sub-indices and it varies across the world based on the definitions of different organizations as mentioned by Senthivel and Chidambaranathan (2022). The purpose of this categorization is to communicate and inform the population about the concentrations of monitored pollutants and their possible harmful effects on health. USEPA determined that the AQI would be calculated by the formula:

$$AQI = I_{in} + \frac{I_{fn} - I_{in}}{C_{fn} - C_{in}} \times (C - C_{in})$$

Where,

I_{in} = the index breakpoint conforming to C_{in}

I_{fn} = the index breakpoint conforming to C_{fn}

C_{in} = the concentration breakpoints < C

C_{fn} = the concentration breakpoints $\geq C$

C = concentration of pollutants

USEPA categorizes the AQI into six levels according to the standards defined by the World Health Organization (AirNow, 2023). For ozone a conversion was necessary as values in AQI are considered in ppm, so we applied the conversion proposed by Boguski (2006). Table 2 shows the linear segmented relationship for sub-index values, the corresponding pollutant concentrations, and the health effects expected.

3. Results

The occurrence of wildfires was shown to significantly affect the levels of the pollutants analyzed in Sinop. For the pollutant O₃, the mean values of all groups in which there were days with fires (Day 0 to Day 5), differed from the mean values of the non-

wildfire days group. On the other hand, for the particulate matter, PM_{2.5} and PM₁₀, significant differences were found only between the group of non-wildfire days, and the groups Day 3, Day 4, and Day 5 (Fig. 2).

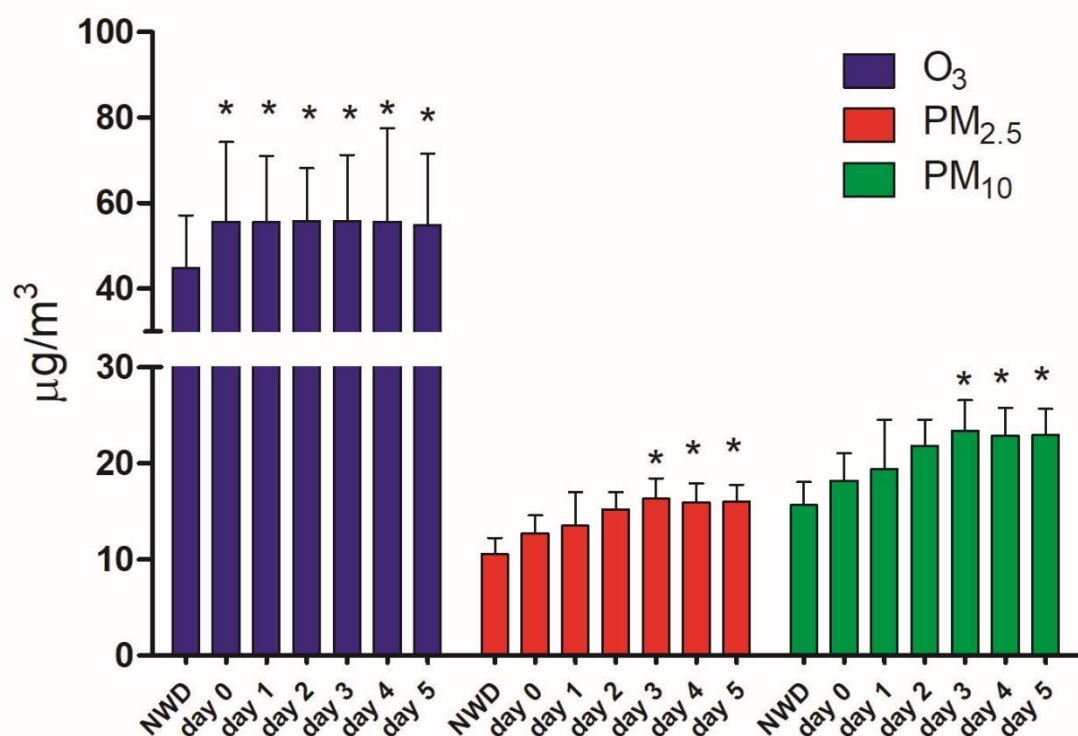


Fig. 2. Air pollutants levels in non-wildfire days (NWD) and from the first day when fires occurred (day 0) to 5 days after (day 5).

The data on the number of fire spots (fire foci) and FRP are shown in Figures 3 and 4. There were fires throughout the year, but after the first four months of the year, fires became more frequent and peaked between the 236th and 257th days of the year, which are in August and September. At the same time, higher FRP values were also verified, namely 104.5 MW and 342.9 MW, both classified as moderate to high intensity. However, the most critical FRP value collected was measured on June 27th and was 652.2 MW. Both the number of fires and FRP values showed a significant effect on O₃ levels ($p = 0.021$, and $p = 0.02$, respectively). On the particulate matter levels, these indicators had no statistically significant influence.

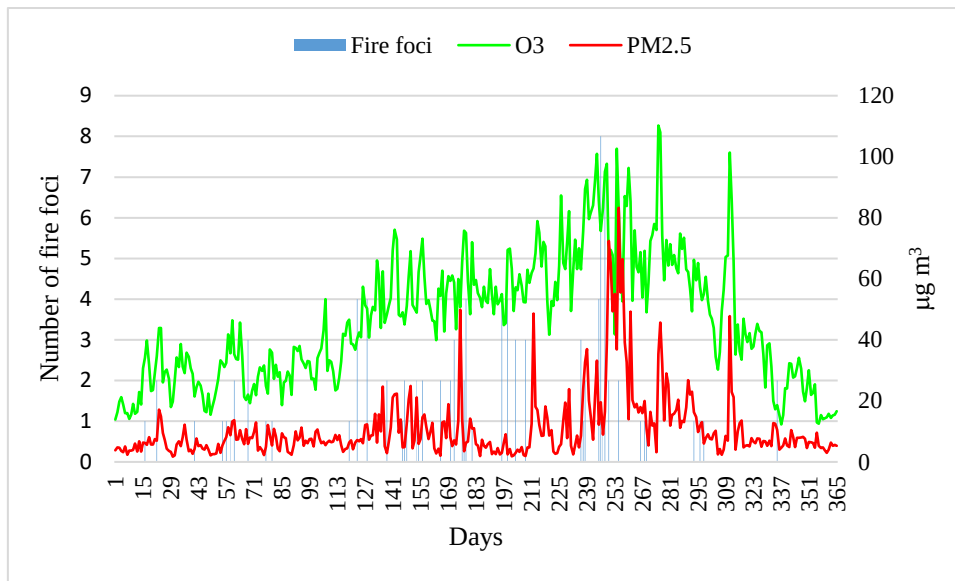


Fig. 3. Occurrence of fire foci and levels of O₃ and PM_{2.5} in Sinop in 2022.

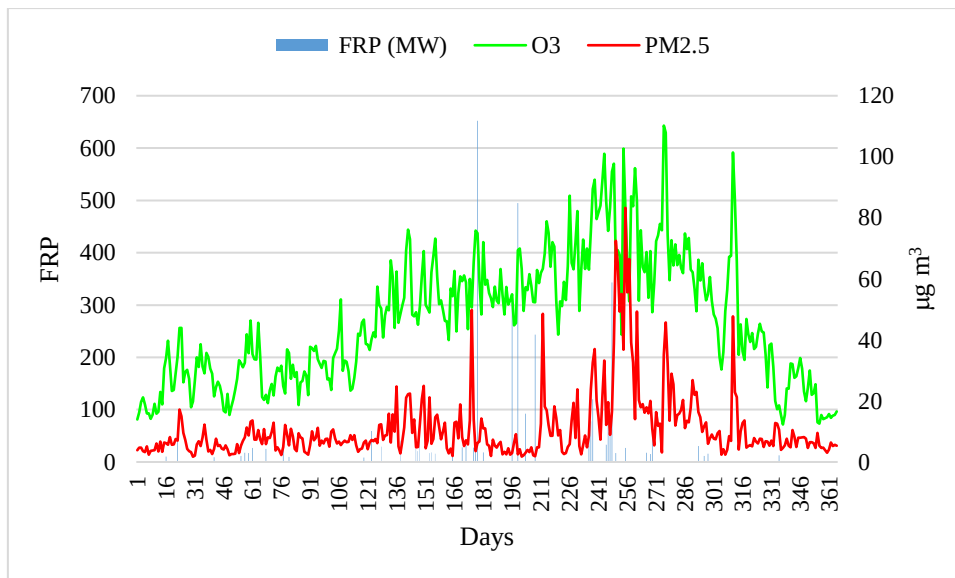


Fig. 4. Fire radiative power (FRP) during wildfire episodes and levels of O₃ and PM_{2.5} in Sinop in 2022.

The existing correlations between the meteorological variables and air pollutants in the presence or absence of fires can be verified in Tables 3, 4, and 5. Temperature showed a significant positive correlation with the three pollutants, both in the absence of fires and on the days when fires occurred. Wind speed displayed a positive correlation with ozone in most scenarios considered but did not affect PM_{2.5} and PM₁₀. Similarly, O₃ was negatively correlated with precipitation, but neither PM_{2.5} nor PM₁₀ were correlated with this variable. Regarding humidity, there was a negative correlation for the three

pollutants, but ozone proved to be more affected by this parameter than particulate matter. Moreover, atmospheric pressure and UV radiation index did not show a strong correlation with any of the pollutants, although significant results were demonstrated. For non-wildfire days, the percentage of days in each of the four quartiles is quite homogeneous for the concentration of the three pollutants, as can be seen in Table 6. Despite that, for O_3 this scenario changes significantly given the days with fire events, where the number of days in Q3 and Q4 increased significantly compared to Q1, denoting that there is a greater number of days when ozone levels were among the highest 50% detected during the evaluated period (Chi-square for tendency test - $\chi^2 = 16.51$ and $p < 0.0001$). For particulate matter this difference almost did not happen and was not significant ($PM_{2.5}$ Chi-square for tendency test - $\chi^2 = 1.14$ and $p = 0.29$ / PM_{10} Chi-square for tendency test - $\chi^2 = 0.57$ and $p = 0.45$).

During the period studied, wildfires were recorded in the region on 47 days. On six occasions, in May (1), June (2), August (1), and September (2), the fires occurred on consecutive days, without interruption. Figures 5, 6, and 7 show the AQI results by percentage of days within each classification level for the pollutants we evaluated.

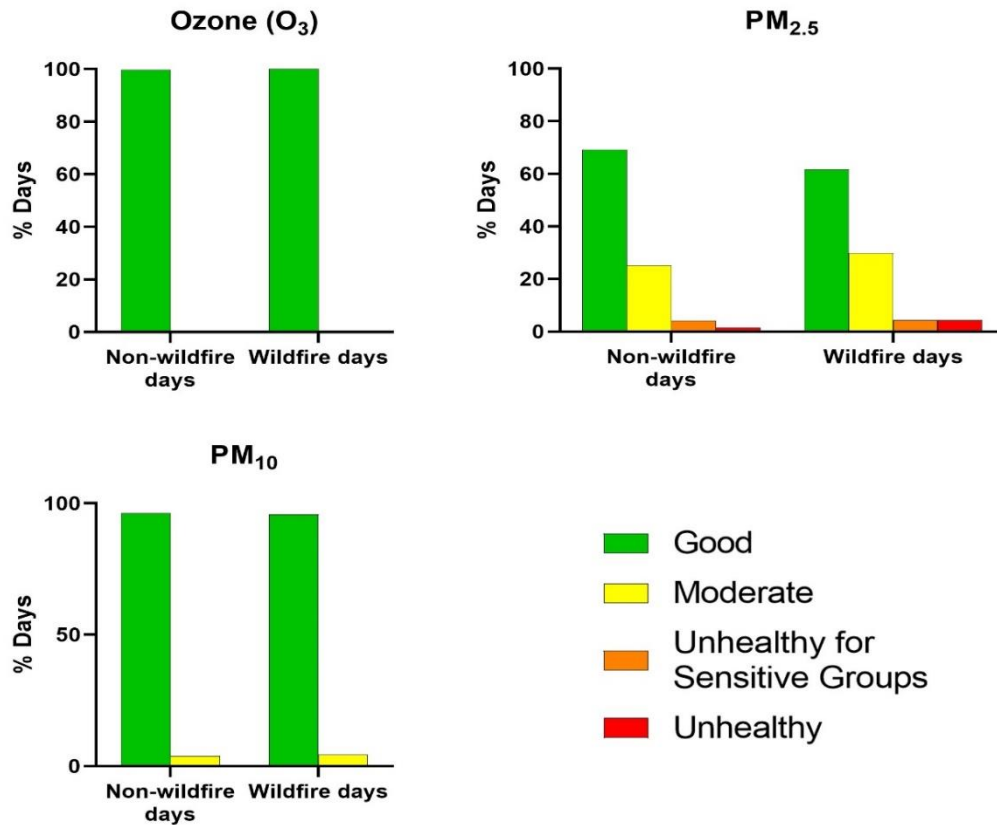


Fig. 5. Air quality index variations for O₃, PM_{2.5}, and PM₁₀ on wildfire and non-wildfire days.

According to the AQI classification, O₃ levels on days without fires (318 days) remained predominantly classified as good), with only 1 day classified as moderate. Regarding PM_{2.5}, on days without burning occurrences, about 74.2% were classified as good, 21.1% as moderate, and 3.7% as unhealthy for sensitive groups. PM₁₀ levels were classified as good on 306 days and normal on the remaining 12 days. On the other hand, the AQI results on days with burning showed a slight increase in the number of days classified as moderate for PM_{2.5} and PM₁₀. For PM_{2.5}, moderate days increased by 0.5 percentage points, and days classified as unhealthy increased by 2.69 percentage points.

Principal component analysis (PCA) was used to reveal patterns and correlations within the data. The PCA results for days with and without wildfires can be seen in Supplementary 1 and 2, respectively. In both cases, the contribution of the two axes explains more than 60% of the data variance. In this sense, it can be observed that regardless of the occurrence of forest fires, humidity, and precipitation show a negative

correlation with O_3 , while the temperature and UV index are positively correlated with both O_3 and $PM_{2.5}$.

4. Discussion

The present study aimed to investigate the multiple effects and consequences of fires on the dynamics of air pollutants in Sinop, a reference center in the North of Mato Grosso (Vieira et al., 2015), on the border between the Brazilian Amazon and Cerrado. Throughout its history, the State of Mato Grosso has undergone transformations that drastically modified its land coverage, and the economic activities that predominate in the region, are recognized for having environmental impacts (Simões et al., 2020), with wildfires being a frequent occurrence.

To the best of our knowledge, this is also the first research to date to investigate the implications of fires on air pollution in this city. Despite the severity of the scenario, Sinop, as well as the other cities in Mato Grosso, do not have an integrated system for monitoring air quality (Vormittag et al., 2021), compromising data collection and making it difficult to measure the actual levels of pollution and their impacts on health. Hence, three central aspects can be highlighted from the results we obtained: 1) the dynamic influence of wildfires on pollutant levels; 2) the temporal patterns of fire occurrence and FRP, and 3) the interplay of meteorological factors and pollutant mobility and concentration.

Concerning the effects of wildfires on atmospheric mobilizations and composition, notably, the temporal patterns of O_3 levels post-fire events reveal a complex interrelationship that merits thorough examination. In Sinop, the O_3 levels rose immediately after the occurrence of wildfires and remained high for the next five days. This is consistent with the study by Targino et al. (2019), which emphasizes that up to 41% of the O_3 found in air pollution in Brazil may originate from forest fires. Similarly, Kalashnikov et al. (2020) pointed out that the occurrence of elevated ozone levels in urban areas in the western United States is related to the occurrence of wildfires. It is common for ozone to be depleted near the fire site by the formation of new NO molecules, while downwind the $NO_2 + VOCs$ cycle is established, contributing to the increase in O_3 (Langford et al., 2023). This also helps to explain why elevated levels of ground-level ozone can persist longer, as more stable compounds formed from NO_x , such as peroxyacyl nitrates (PANs), are eventually degraded (Bourgeois et al., 2021).

Our results corroborate previous works that underlined the intricate connection between wildfires and heightened O_3 levels (McClure and Jaffe, 2018; Pope et al., 2019). Such heightened O_3 concentrations during and following the first days after fire events may be attributed to the photochemical reactions involving the compounds released during combustion processes (Targino et al., 2019) that can induce such raises even out of O_3 season peaks. Despite that, this relationship is still the subject of investigation by the scientific community (Lu et al., 2021).

The effects were somewhat different for $PM_{2.5}$ and PM_{10} . For these pollutants, the response occurred slightly later than for ozone, and it was not until the third day after the fires that there was a significant increase in particulate matter concentrations, which persisted on days 4 and 5. McClure and Jaffe (2018) also described high levels of O_3 preceding significant increases in particulate matter concentrations, and in conditions with heavy smoke formation, O_3 levels tend to decrease. Variations in emissions result from different combustion conditions, which include factors such as fuel properties, combustion temperature, combustion phase (whether flaming or smoldering), moisture content, and weather variables (Kalogridis et al., 2018). An example of this is the study by Yang et al. (2020), which demonstrated that the effects of meteorological variables on air pollutants can be persistent. Under the conditions investigated in their research, precipitation and wind speed influenced $PM_{2.5}$ levels for up to four days.

Similarly, Tavella et al. (2022) observed that PM_{10} and $PM_{2.5}$ levels decreased dramatically in the case of the mini-lockdown in the city of Pelotas-RS, and even after the resumption of activities, these levels remained reduced for several days, also suggesting a time lag in the dynamics of these pollutants. Although soybean-growing areas in the Amazon biome are known to produce high levels of particulate matter during fires (Cobelo et al., 2023), the complexity of factors leading to the formation of these compounds in the atmosphere could contribute to the lagged increase we verified. In addition, the study by Costa et al. (2022) is valuable as it shows that in the initial stages of a forest fire (flaming), submicrometric size particles (size $< 1 \mu m$) tend to predominate, which are more difficult to detect, and when the fire moves into the smoldering phase, the smoke aging process leads to an increase in particle size. Taking into account the new air quality standards recently established by the World Health Organization (WHO, 2021) which predict daily averages of $15 \mu g m^{-3}$ and $45 \mu g m^{-3}$ for $PM_{2.5}$ and PM_{10} , respectively, and $100 \mu g m^{-3}$ for O_3 every 8h, and up to $60 \mu g m^{-3}$ in the peak season, the levels verified

in Sinop went above the recommendation in various occasions, especially during wildfire days.

Figures 3 and 4 provide a vivid depiction of temporal fire patterns and their synergy with FRP values. The concentration of fire incidents during August and September, coupled with the identification of moderate to high FRP values, reinforces the potential for intense combustion and consequential heat release. Markedly, the correlation between FRP values and ozone levels demonstrates FRP's utility as an indicator of fire intensity and its subsequent ramifications for air quality (Fisher et al., 2020). One of the hypotheses that may help explain this relationship is the apparent positive correlation between the increase in FRP and the increase in NO₂ and nitrous acid (HONO) levels, both compounds released during combustion that can participate in the chemical reactions that take place in the atmosphere in the presence of sunlight and act as precursors of ground-level O₃ and particulate matter, as Fredrickson et al. (2023) mentioned. In particular, for fires with FRP < 400 MW, which include most of the episodes that occurred in Sinop in 2022, this relationship appears to be consistent worldwide.

The fire radiative power can also positively correlate with the particulate matter, as shown by Ohashi et al. (2021) and Son et al. (2023). The lack of correlation between FRP and particulate matter in our study may be due to the short time series examined, as according to Price et al. (2012), data from several decades may be required to verify the relationship between FRP and the level of air pollutants. Son et al. (2023) also emphasized that fires alone cannot always be the direct cause of the elevated PM_{2.5} levels, as periods of high particulate matter concentrations in the atmosphere can occur while low FRP levels are detected. This linkage is still very little explored in Brazil's investigations on air pollution, however, this indicator seems to be a very interesting method in biomass burning emissions estimation (Li et al., 2020).

The temporal progression of fire incidents holds implications that extend beyond statistical observations, as fires can be considered an essential climatic variable (Laurent et al., 2019) with undeniable impacts on heat wave formation, and climate change (Oliveira et al., 2022). These patterns suggest the need for preparedness during the months of increased fire activity. Additionally, these findings prompt a closer examination of underlying drivers—climatic, ecological, or anthropogenic—that contribute to the observed temporal trends, as this region is continuously described as of high density of fire foci (Oliveira-Júnior et al., 2021).

Regarding the analysis of correlations between meteorological variables and pollutants, it helps to elucidate the interdependencies between atmospheric parameters and pollutant levels. Temperature's persistent positive correlation with all three pollutants emphasizes its role in reactions and emissions. This scenario points to the disastrous consequences of global warming associated with increased atmospheric pollution (Moura and Da Silva Júnior, 2023). Also, the positive relationship between wind speed and ozone concurs with the dispersal of pollutants over larger areas during fire events (Urrutia-Pereira et al., 2021). Humidity's negative correlation with pollutants is probably related to its influence on chemical transformations and deposition processes (Kavassalis and Murphy, 2017). Despite this considered positive effect, increased humidity levels in fire episodes can be problematic both by dragging pollutants such as particulate matter closer to the ground, facilitating its inhalation (Airly, 2023), as well as by triggering a phenomenon called "superfog" which causes visibility to be extremely impaired and may lead to transportation hazards (O'Neil et al., 2017). Yet, the complexity of these relationships necessitates further investigation, potentially encompassing detailed chemical kinetics simulations and field campaigns to tease apart the underlying mechanisms.

About the AQI results, it should be noted that when converting the ozone values to ppm, values corresponding to the classification "moderate" were only achieved on one day (October 10th), while the PM_{2.5} standards changed only slightly, but not significantly. Intriguingly, the quartile analysis further enriches our understanding of the observed AQI variations. The homogeneity in the distribution of pollutant concentrations during non-wildfire days across quartiles demonstrates quite stable air quality conditions. However, for ozone this pattern shifted during wildfire events, with a noticeable increase in days falling within the third and fourth quartiles even though no differences were seen in AQI index. This reinforces the greater occurrence of elevated pollutant levels during wildfire episodes. The juxtaposition of AQI trends and quartile illustrates how wildfire-induced variations disrupt the distribution of pollutant concentrations (Son et al., 2023).

These integrated findings provide a comprehensive perspective on the multiple impacts of wildfires on air quality, from the underlying atmospheric processes to their tangible implications for public health and urban environments, which are usually difficult to control and predict. This approach fosters a deeper understanding of the dynamic interplay between wildfires, meteorology, and pollutant concentrations,

empowering policymakers and researchers alike to develop more effective strategies for managing air quality during and after wildfire events.

Some limitations of this study must be acknowledged. First, the variables on wildfires, air pollution, and weather were either determined by satellite remote sensing or derived from models using satellite data, especially the air pollution data for which there is also no local monitoring information. This can lead to certain inaccuracies in the measurements. All fire data provided by the INPE were calculated as wildfires, making it impossible to determine their origin or if they were deliberately lit fires. Furthermore, as this is a relatively short study covering one year, the data we reviewed may be singular and a larger data set collected over a broader study period could corroborate the results obtained or even provide new insights that we were unable to verify. Although it is known that the emission of pollutants from fires is usually limited to hours or days, the constancy of their occurrence and the long-term effects of exposure to high levels of air pollutants underline the importance of studies such as this one.

5. Conclusions

In this study, the impact of wildfires on air quality in Sinop was investigated, revealing significant findings with implications for the field. The analysis demonstrated that wildfires had an important influence on pollutant levels, particularly for ozone, where mean values during days with fires significantly differed from non-wildfire days. The occurrence of fires and their intensity, measured through FRP, peaked in August and September, coinciding with the highest O₃ levels. However, particulate matter exhibited significant differences only between non-wildfire days and specific wildfire days. Meteorological factors like temperature, wind speed, humidity, and precipitation exhibited varying correlations with pollutants, with temperature displaying a consistent positive correlation. Additionally, the AQI revealed a degradation in air quality on days with wildfires, particularly for O₃, emphasizing the environmental impact of these events.

The findings collectively call attention to the significance of interdisciplinary approaches in understanding and addressing the complex relations between wildfires and atmospheric pollutants. These insights unveil the variety of parameters that must be considered in devising holistic air quality management strategies, particularly in regions vulnerable to frequent and intense fire events, such as the Cerrado-Amazon ecotone.

Moreover, our results help to set the stage for future research endeavors. The temporal patterns of fire occurrences demand a nuanced exploration of the factors that act over fire activity during peak months. The role of FRP as an intensity indicator shows the potential for its integration into predictive models for fire-related air quality degradation. The meteorological-pollutant relationships call for an approach that combines numerical simulations, remote sensing, and ground-based observations to unravel the underlying mechanisms which are still very scarce in the region.

In conclusion, the current study offers a foundation for decision-makers in considering new politics for facing and better-managing air quality during fire events, with far-reaching implications for environmental policy, public health, and scientific advancement.

Credit author statement

Fernando Rafael de Moura: Methodology, Formal analysis, Writing – Original Draft, Writing – Review & Editing; Petter Djeison Witte Machado: Writing – Review & Editing; Ronan Adler Tavella: Writing – Review & Editing; Paula Florencio Ramires: Writing – Review & Editing; Helotonio Carvalho: Writing – Review & Editing; Flávio Manoel Rodrigues da Silva Júnior: Visualization, Methodology, Software, Formal analysis, Resources, Writing – Review & Editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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1 **Tables**

2

3 **Table 1** - Summary of the various data sources used in this study.

Category	Source product	Temporal resolution	Spatial resolution
Air quality	PM _{2.5} , PM ₁₀ , O ₃	hourly	point
Weather	Temperature	monthly	25 km
	Wind velocity	monthly	25 km
	Relative humidity	monthly	25 km
	Atmospheric pressure	monthly	25 km
	UV radiation index	monthly	25 km
	Precipitation	monthly	25 km
Wildfire (fire foci, FRP)	NASA Terra/Aqua MODIS	daily	1 km
	NOAA-18/NOAA-19	daily	1.1 km
	Suomi NPP VIIRS	daily	5 km
	NOAA-20	daily	750 m
	METOP-B	daily	5.5 km
	GOES-16	hourly	4 km
	MSG-3	hourly	3 km

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8 **Table 2** - Impacts on health verified in conditions of deviations in air quality.

USEPA AQI Level	Index	O ₃ (ppm) 8h	PM _{2.5} (µg m ³) 24h	PM ₁₀ (µg m ³) 24h	Health recommendations (24h exposure)
Good	0-50	0-0.054	0-12	0-54	Air quality is good and poses little to no risk.
Moderate	51-100	0.055-0.07	12.1-35.4	55-154	Air quality is acceptable but is a concern for sensitive people who should avoid outdoor activities.
Unhealthy for sensitive groups	101-150	0.071-0.085	35.5-55.4	155-254	Air quality is unhealthy for many people. Sensitive groups may suffer negative health effects while the general public is less likely to be affected.
Unhealthy	151-200	0.086-0.105	55.5-150.4	255-354	Air quality is bad. The general public may face negative health effects while sensitive groups are likely to have more serious problems. Strenuous outside activities must be avoided.
Very unhealthy	201 - 300	0.106-0.2	150.5-250.4	355-424	Air quality is unhealthy for everyone. The risk of negative health effects is high, especially for people with heart and/or lung diseases.
Hazardous	301 - 500	>0.21	>250.5	>425	Air quality is hazardous. It is an emergency condition: everybody is likely to be affected and people should stay indoors.

10 **Table 3** – Correlations between meteorological variables and occurrence of wildfires for O₃ levels.

		All days	Non-wildfire days	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5
Temperature (°C)	<i>r</i>	0.60	0.59	0.59	0.61	0.59	0.59	0.62	0.59
	<i>p</i>	<0.01	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Wind speed (m s ⁻¹)	<i>r</i>	0.21	0.18	0.43	0.51	0.49	0.32	ns	0.56
	<i>p</i>	<0.001	=0.01	=0.003	<0.001	=0.001	=0.03		<0.001
Humidity (%)	<i>r</i>	-0.76	-0.75	-0.78	-0.80	-0.73	-0.77	-0.76	-0.76
	<i>p</i>	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Pressure (hPa)	<i>r</i>	0.34	0.29	ns	ns	0.33	ns	0.33	ns
	<i>p</i>	<0.001	<0.001			=0.02		=0.02	
UV radiation index	<i>r</i>	0.23	0.25	ns	ns	ns	ns	0.33	ns
	<i>p</i>	<0.001	<0.001					=0.02	
Precipitation (mm)	<i>r</i>	-0.23	-0.21	-0.39	-0.34	ns	-0.37	-0.46	ns
	<i>p</i>	=0.04	<0.001	=0.007	=0.02		=0.01	=0.001	

11 Bold values indicate *r* values with statistical significance ($p < 0.05$).

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14 **Table 4** – Correlations between meteorological variables and occurrence of wildfires for PM_{2.5} levels.

		All days	Non-wildfire days	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5
Temperature (°C)	<i>r</i>	0.43	0.45	0.33	0.59	0.36	0.44	0.43	0.45
	<i>p</i>	<0.001	<0.001	=0.03	<0.001	=0.01	=0.002	=0.003	=0.01
Wind speed (m s ⁻¹)	<i>r</i>	ns	ns	ns	ns	ns	ns	ns	ns
	<i>p</i>								
Humidity (%)	<i>r</i>	-0.31	-0.34	ns	-0.30	ns	ns	-0.37	0.29
	<i>p</i>	<0.001	<0.001		=0.04			=0.01	=0.04
Pressure (mb)	<i>r</i>	0.23	ns	ns	ns	ns	ns	ns	ns
	<i>p</i>	<0.001							
UV radiation index	<i>r</i>	0.27	0.30	ns	0.45	ns	ns	ns	ns
	<i>p</i>	<0.001	<0.001		=0.002				
Precipitation (mm)	<i>r</i>	ns	ns	ns	ns	ns	ns	ns	ns
	<i>p</i>								

15 Bold values indicate *r* values with statistical significance ($p < 0.05$).

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21 **Table 5** – Correlations between meteorological variables and occurrence of wildfires for PM₁₀ levels.

		All days	Non-wildfire days	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5
Temperature (°C)	<i>r</i>	0.39	0.41	0.33	0.59	0.36	0.45	0.43	0.45
	<i>p</i>	<0.001	<0.001	=0.03	<0.001	=0.01	=0.002	=0.003	=0.01
Wind speed (m s ⁻¹)	<i>r</i>	ns	ns	ns	ns	ns	ns	ns	ns
	<i>p</i>								
Humidity (%)	<i>r</i>	-0.28	-0.29	ns	-0.30	ns	ns	-0.38	0.29
	<i>p</i>	<0.001	<0.001		=0.04			=0.01	=0.04
Pressure (mb)	<i>r</i>	0.23	ns	ns	ns	ns	ns	ns	ns
	<i>p</i>	<0.001							
UV radiation index	<i>r</i>	0.27	0.29	ns	0.45	ns	ns	ns	ns
	<i>p</i>	<0.001	<0.001		=0.002				
Precipitation (mm)	<i>r</i>	ns	ns	ns	ns	ns	ns	ns	ns
	<i>p</i>								

22 Bold values indicate *r* values with statistical significance ($p < 0.05$).

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Table 6 - Differences in the frequency of days according to air pollutants concentrations (in quartiles) during wildfire or non-wildfire days.

Classification		Air pollutants				
		O ₃		PM _{2.5}		PM ₁₀
Non-wildfire days		n	%	n	%	n
Q1		87	27.4	82	25.8	82
Q2		83	26.1	81	25.5	79
Q3		76	23.9	78	24.5	81
Q4		72	22.6	77	24.2	76
<i>p</i> for trend			ns		ns	ns
Wildfire days						
Q1		4	8.5	9	19.1	11
Q2		9	19.1	13	27.7	11
Q3		15	31.9	11	23.4	11
Q4		19	40.4	14	29.8	14
<i>p</i> for trend			*		ns	ns

**p* for trend showed statistical significance. ^{ns}*p* for trend showed no statistical significance.

6.3 Manuscrito III

Status	Submetido
Periódico	The image shows the front cover of the journal 'Environmental Research'. At the top left is the Elsevier logo. The title 'environmental research' is prominently displayed in the center, with 'environmental' in red and 'research' in green. Below the title is a large, colorful illustration divided into three horizontal bands: a green band at the top showing a city skyline, an orange band in the middle showing a desert landscape with rocks, and a green band at the bottom showing a lush agricultural field with a small white and red airplane flying over it. At the top right of the cover, it says 'Volume 255 15 August 2024 ISSN: 0013-9351'. At the bottom of the cover, the journal title 'Environmental Research' is repeated in a smaller font.
Fator de impacto (JCR 2022)	8.3

Amazon's climate crossroads: Analyzing air pollution and health impacts in the Northern Mato Grosso, Brazil

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Abstract

Air pollution has long been an issue in South America, with historical roots going back more than two centuries. Of great importance is the link with climate change and its various health effects. In Brazil, despite recent advances in the quantification and monitoring of air pollutants, there are still significant gaps, which are exacerbated by an inadequate monitoring infrastructure. This is particularly pronounced in small and medium-sized cities outside the metropolitan areas, where air quality is often below international standards. In this context, the Amazon rainforest, an important global climate regulator, is facing unprecedented challenges due to rising temperatures, deforestation, and forest fires. Sinop, located in the heart of the Amazon biome in Mato Grosso, offers a unique vantage point for studying the interplay between agricultural expansion and air pollution. This study aimed to present a comprehensive investigation of the meteorological data, air pollutants, and their possible health effects in Sinop. The pollutants investigated were particulate matter (PM) from 2.5 to 10 μm (PM_{2.5} and PM₁₀) and ground-level ozone (O₃). We performed the Health Impact Assessment (HIA) methodology using AirQ+ software and simulations of temperature rise scenarios using a machine learning technique with data from the year 2022. The results showed that ground-level ozone reacts very sensitively to meteorological parameter alterations in the region. The highest

temperature increase scenario was associated with an increase of almost 50% and 70%, in PM_{2.5} and PM₁₀, respectively. Under these conditions, the number of deaths related to air pollution can become a significant social and economic burden for the region. Considering this background, our results endorse the urgent need for proactive measures to monitor air quality and mitigate the negative effects of air pollution, especially in rapidly urbanizing regions such as Sinop.

Keywords: AirQ+, Estimation, Health impact assessment, Machine learning, Mortality, Temperature

1. Introduction

Air pollution is an ancient phenomenon in South America. Andean people were emitting toxic trace elements into the atmosphere through metallurgical activities more than 200 years before the Industrial Revolution began in Europe (Uglietti et al., 2015). However, it was not until the occurrence of historical environmental disasters such as air pollution in the Meuse Valley in Belgium (1930) or the severe smog episodes in Los Angeles after 1940, that debates about human impact on nature began to emerge from the second half of the 20th century (Pott and Estrela, 2017; Zhang et al., 2022).

Since then, this topic has attracted the scientific community's attention because of its almost innumerable implications. Despite that, two major research areas have gained importance concerning air pollution, mainly because of the urgency and severity of its consequences which are: climate change and the relationship between pollutants and various health problems (Manisalidis et al., 2020; Alahmad et al., 2023). In Brazil, the interest in this environmental challenge can be considered new, since it was only between the 1980s and 1990s that the first clear initiatives to quantify and monitor air pollutants emerged (Valadão et al., 2022).

Regarding climate change, researchers point to its close relationship with air pollution (Figueres et al., 2018; Keswani et al., 2022; Leão et al., 2023). Burning activities, whether fossil fuels to service the vehicle fleet (high and middle-income countries) or biomass (as occurs in forest fires and domestic environments), in low-income countries, are identified as the main causes of accumulation of pollutants in the atmosphere and their harmful effects on the climate (Whitmee et al., 2015; Moura et al., 2024).

Such changes in the atmosphere pose a risk to a variety of organisms and have implications for human society. Talukder et al. (2022) emphasized that processes such as acidification, deoxygenation, and ocean warming, which are classified as direct consequences of climate change, contribute to a variety of other impacts ranging from alterations in hydrological cycles (Li et al., 2022), loss of biodiversity (Habibullah et al., 2022), and even the emergence of new pandemics (Baker et al., 2021) or an increase in toxic animal accidents (Martinez et al., 2022; Souza et al., 2022).

Also, from a public health perspective, the World Health Organization (WHO) points out that 97% of residents of urban areas in low- and middle-income countries live in unhealthy air quality conditions, which is not in line with international recommendations (WHO, 2018). Particulate matter air pollution was the leading contributor to the global disease burden in 2021 according to GBD 2021 Risk Factors Collaborators (2024). Considering that in many of these countries, including Brazil, air quality monitoring is inadequate and scarce (WHO, 2021; Krecl et al., 2023), there are still many information gaps, both in the quantification of these impacts and in the adoption of new guidelines (De Moura and Da Silva Júnior, 2023a).

It happens whether due to the pressure created by the update of the proposed standards by the WHO in 2021, or due to recent insights from studies such as that of Vilcassim and Thurston (2023), which point out the importance of monitoring particles such as PM₁, since they are even more harmful than PM_{2.5}, but whose identification is beyond what has been accomplished by the Global South (De Moura and Da Silva Júnior, 2023b).

Despite the difficulties encountered in predictive models (Pozzer et al., 2022), recent research consistently indicates that illness, public health costs, and workplace productivity losses are increasing due to increments in concentrations of air pollutants (Aguilar-Gomez et al., 2022; Barboza et al., 2022; World Bank, 2022). Neurodegenerative disease, heart and respiratory disease, infertility, and reduced life expectancy are health problems that are associated with exposure to various pollutants such as ozone (O₃), particulate matter (PM_{2.5} and PM₁₀) sulfur and nitrogen oxides (SO_x and NO_x), and carbon monoxide (CO) (Lelieveld et al., 2020; Calderón-Garcidueñas and Ayala, 2022; Margiana et al., 2022; Sousa et al., 2022; Lo et al., 2023).

From this perspective, the Amazon rainforest, one of the most important ecosystems on Earth, has undergone unprecedented changes in recent years. Among these changes, temperature increase, deforestation, and wildfires are some of the main environmental challenges (B. Oliveira et al., 2021; Drüke et al., 2023). This region is considered a crucial global climate regulator, influencing weather patterns far beyond its borders (Ellwanger et al.,

2020). Oliveira et al. (2023) also emphasized that the North and Central-West regions of Brazil, with a population of more than 40 million people, are frequently exposed to high levels of air pollution throughout the year, which are generally not of industrial origin. This scenario, which differs from that of large metropolitan areas, is exacerbated by the limited access to information and the lower perception of the risks associated with such exposure on the part of the local population.

Located in the heart of the Amazon biome, Sinop, in northern Mato Grosso, is a medium-sized city that has experienced significant growth in recent decades, driven mainly by the expansion of the agribusiness model (Coy et al., 2020). This expansion has brought with it several environmental challenges, especially due to the critical interface with the Cerrado biome, which is already prone to frequent fires due to dry vegetation (Li et al., 2021). Sinop's proximity to these transitional areas between the Amazonian biome and the Cerrado places it in a unique position to study the effects of agricultural expansion, air pollution, and forest fires, which, along with the loss of the municipality's original natural areas, are among the critical elements contributing to the ecological vulnerability of this region. Recently, our group have already studied the burning impacts of air quality in Sinop, but at that time we did not evaluate the health outcomes (Moura et al., 2024).

So far, there are no studies that have analyzed such issues in this city. Therefore, this article presents an examination of meteorological data, atmospheric pollutants (O_3 , $PM_{2.5}$, and PM_{10}), and their potential repercussions on cardiorespiratory mortality within Sinop. By integrating health-related information with environmental parameters, this study aims to uncover plausible associations between air quality, climate change, and public health. Moreover, through the simulation of future climate scenarios, we seek to offer valuable insights into the environmental resilience of this region.

2. Material and methods

2.1 Study site

Sinop is in the north of the State of Mato Grosso, in the Central-West region of Brazil (Fig. 1). Being the fourth largest municipality in the state, it has a population of approximately 200 thousand inhabitants according to the Brazilian Institute of Geography and Statistics (IBGE, 2022), and an HDI of 0.754. It borders the Cuiabá-Santarém Federal Highway, called BR-163 (Rodrigues and Nahum, 2023), a crucial path for agribusiness production flow (Soliani,

2022). Together with the municipalities of Lucas do Rio Verde, Nova Mutum, Porto dos
Gaúchos, Santa Carmem, Sorriso, and Tapurah, it is part of the Tourist Route of the
Agribusiness Portal defined by the Regionalization Program of the Brazilian Ministry of
Tourism (Turismo, 2023), which aims to direct investments and public policies for the region
development. In this area, crops such as soybeans, corn, and cotton stand out, and in livestock
farming, poultry and pig production predominates (J. Oliveira et al., 2021).

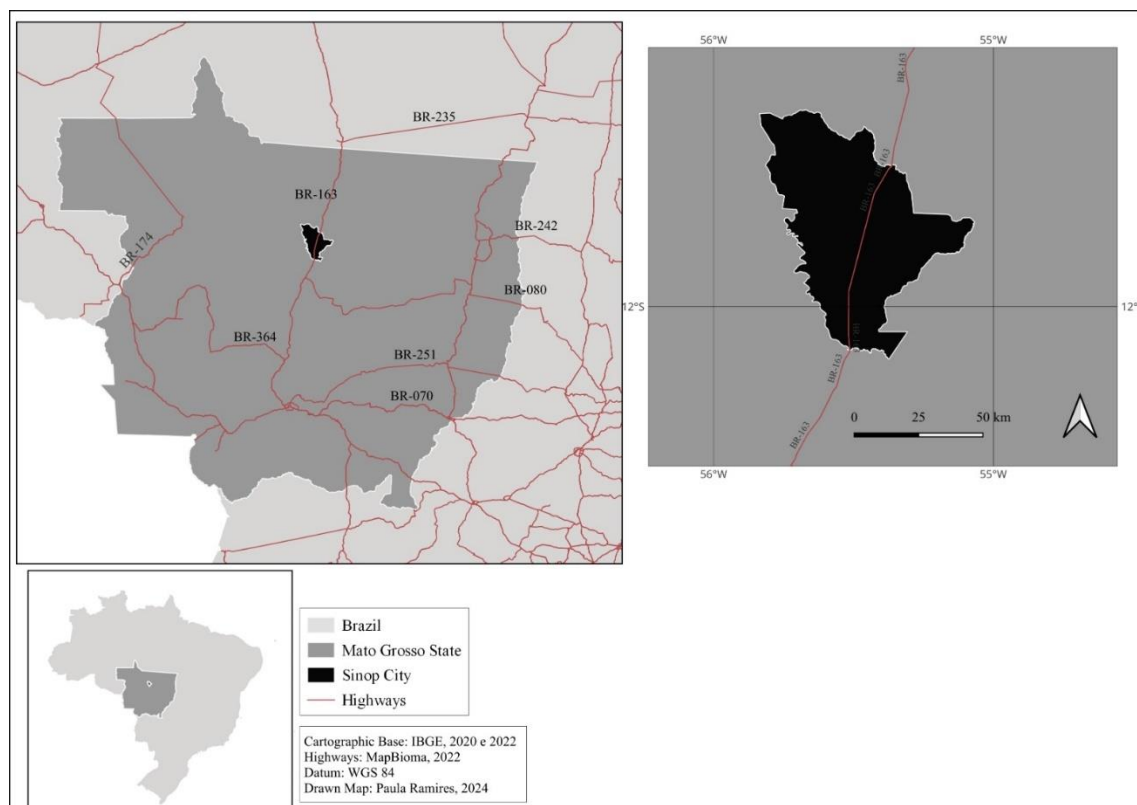


Fig. 1. Map locating Sinop (Mato Grosso, Brazil) and indicating the main highways.

2.2 Data sampling

All data used in this research is public. Concentrations of ozone (O_3), particulate matter ($PM_{2.5}$), and coarse particulate matter (PM_{10}), all expressed in micrograms per cubic meter ($\mu g/m^3$) were obtained from the modeling dataset sourced by the European Center for Medium-Range Weather Forecasts (ECMWF), specifically from the Copernicus Atmospheric Monitoring Service (CAMS). Data extraction was performed daily using the Weather Channel application (<https://weather.com/pt-BR/forecast/air-quality/>) provided by IBM as conducted in other studies (Tavella et al., 2023; Moura et al., 2024). The data resolution was 0.125° (about

12.5 km) and pollution levels were estimated on a daily temporal scale, considering information provided four times a day: 12:00am, 06:00am, 12:00pm and 06:00pm (Oliveira et al., 2023).

It is important to mention that even though CAMS has its limitations regarding the validation and retrieval of accurate pollution data at ground level outside the European continent, several studies have brought consistent data on the use of this tool in Brazil (Brum et al., 2023; Brum et al., 2024; Requia et al., 2021; Tavella et al., 2023). Furthermore, as studies using CAMS as a tool for air pollution and meteorological predictions grow, Gueymard and Yang (2020), showed that CAMS estimates in South America have a root mean square error (RMSE) of 0.268 when compared to Aerosol Robotic Network (AERONET) stations data, which can be considered a reliable source as Requia et al. (2021) also reinforced.

The selection of these pollutants (O_3 , $PM_{2.5}$, and PM_{10}) was based on notable characteristics of the region that have already been highlighted in other studies (Oliveira et al., 2011; Mataveli et al., 2021). In Mato Grosso, forest fires represent one of the main sources of air pollution, in contrast to the exposure profile in the major urban centers (Menezes et al., 2018a; Menezes et al., 2018b). Urrutia-Pereira et al. (2021) also found that the predominant compound in forest fire smoke in the Amazon is PM, especially $PM_{0.1}$. In addition, Castelhana et al. (2022), when evaluating recent changes in weather and air pollution in Brazil, pointed out that CO , SO_2 , and NO_2 emissions decreased in Mato Grosso, while tropospheric ozone increased between 2013 and 2018, accompanied by an increase in temperature. Although polycyclic aromatic hydrocarbons (PAHs) and volatile organic compounds (VOCs) are also frequently emitted during forest fires, they are difficult to track and quantify due to the lack of air quality monitoring stations (Oliveira et al., 2023).

Meteorological data, consisting of daily temperature ($^{\circ}C$), wind speed ($m\ s^{-1}$), humidity (%), atmospheric pressure (hPa), UV radiation index, and precipitation (mm), were collected from an automated station in Sinop ($11^{\circ}87' S$, $55^{\circ}57' W$) at an altitude of 370 meters. These data were obtained from the Agrometeorological Monitoring System (Agritempo) developed by the National Institute of Meteorology (INMET) (<https://www.agritempo.gov.br/br/estado/MT/monitoramento/>) as proposed by Barcellos et al. (2021). The period chosen for data extraction was extended from 01/01/2022 to 12/31/2022.

The information on population and health data (mortality) was extracted from databases available on the websites of the Department of Informatics of the Brazilian Unified Health System/Ministry of Health (DATASUS) (<http://tabnet.datasus.gov.br/cgi/defctohtm.exe?sim/cnv/obt10mt.def>) and IBGE (<https://www.ibge.gov.br/cidades-e-estados/mt/sinop.html>) following Silva et al. (2017),

considering the year 2022. DATASUS is a large secondary database. Although it is an official source of information widely used in Brazilian research, it is sensitive to misdiagnosis and input errors, as its original purpose was to collect financial data (Nascimento and Vieira, 2021; Viana et al., 2023). For the long-term effects associated with the three air pollutants, in addition to the population data (total population and number of people aged over 30 years), mortality from non-external causes (A00-R99) and mortality from respiratory causes (J00-J99) were extracted from TABNET (DATASUS). Mortality data were selected by the main cause of death of the residents living in the study area, as indicated by Abe and Miraglia (2016). We also extracted specific data on cardiovascular mortality (I00-I99) and mortality from ischemic heart diseases (IHD) (I20-I25) for PM_{2.5} and PM₁₀, respectively.

2.3 Temperature-increase scenarios simulations

The machine learning (ML) approach was used to simulate temperature rise scenarios, specifically using the Support Vector Machine (SVM) regression method, which is a supervised algorithm whose purpose is to classify data into two or more categories and is popular in identifying patterns, climatological predictions, or novelty detection (Fan et al., 2018; Su et al., 2020). This method was chosen because it is more advantageous and provides better predictions than other neural network models, as it applies the principle of structural risk minimization and avoids problems such as the overfitting training as reported by Shafii et al. (2020) and T. Liu et al. (2022).

The continuous dependent variables were the pollutant concentrations (O₃, PM_{2.5}, or PM₁₀), while the predictor variables were temperature, wind speed, humidity, atmospheric pressure, UV index, and precipitation. The training sample considered the daily records (weather and pollutants) obtained throughout the study period, using 70%, 15%, and 15% of data for training, validation, and testing respectively (Leong et al., 2020). We used the Classification SVM Type 1 regression, value of seed for sampling was 1000 and kernel type was Radial Basis function (RBF) (Vong et al., 2012). Data processing was carried out using the STATISTICA® program version 12.0. Cross-validation was performed to improve the reliability of the results. A Pearson correlation was also performed to investigate the associations between the meteorological variables and air pollutants, which is in line with other studies (Brum et al., 2024; Yousaf et al., 2024). Statistical significance was assumed at $p < 0.05$.

Considering the influence of the temperature over other meteorological variables, a preliminary simulation of the futuristic atmosphere was performed, using increased temperatures (+0.5 °C, +1.0 °C, +1.5 °C, +2.0 °C, +2.5 °C, +3.0 °C, +3.5 °C, and +4.0 °C) as the independent variable and considering separately each of the meteorological variables that had a significant correlation with temperature as the dependents. After that, for the testing sample (expected values) we simulated each of the pollutants in the eight established temperature increase scenarios, from more realistic to the more alarmist one. We chose these scenarios because they are still conservative given the data published by the Intergovernmental Panel on Climate Change (IPCC), which points to a global temperature increase between 3.3 °C and 5.7 °C by 2100 (Boehm and Schumer, 2023). A brief depiction of the ML process can be found in Fig. 2.

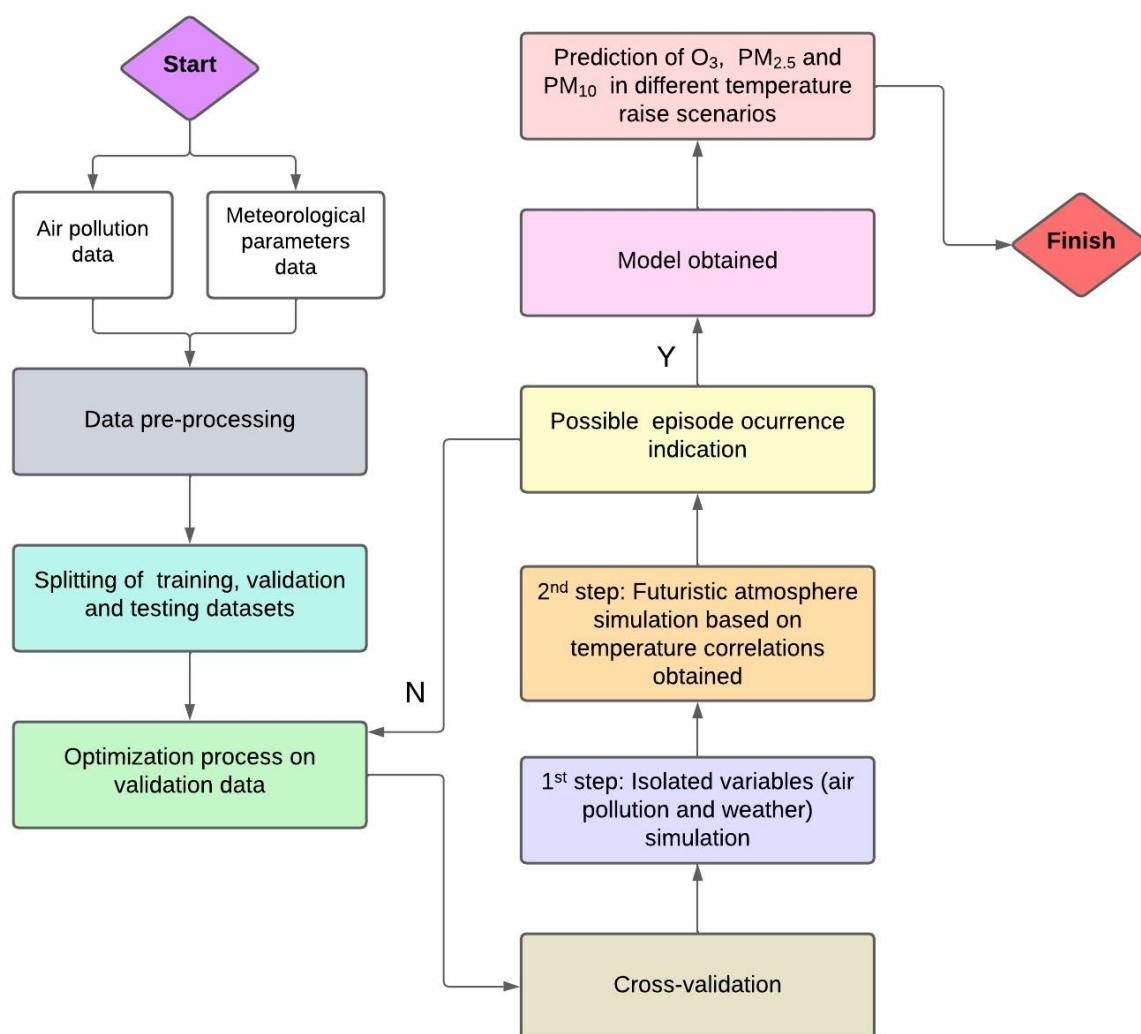


Fig. 2. Flow chart of developed machine learning-based prediction model.

2.4 Health Impact Assessment (HIA)

We assessed the health outcomes of pollutant concentrations on the baseline levels found in Sinop in 2022, and the levels obtained after the temperature increase simulations, considering the new cut-off limits proposed by the WHO as the new Air Quality Guidelines (AQGs) in 2021 (5 $\mu\text{g m}^{-3}$ for $\text{PM}_{2.5}$, 15 $\mu\text{g m}^{-3}$ for PM_{10} , and 100 $\mu\text{g m}^{-3}$ for O_3). We utilized the AirQ+ software (version 2.2.4) established by WHO to conduct health impact assessments for long-term effects based on temporal trends for $\text{PM}_{2.5}$, PM_{10} , O_3 , and other pollutants. This is a useful tool, and it can be applied for any region to evaluate how much a specific health outcome (in terms of mortality or morbidity) is attributable to certain air pollutant concentrations and the health effects if levels change in the future compared to the present (Naghan et al., 2022; Wikuats et al., 2023). The deaths attributed to air pollution were obtained based on the following equations (Cakaj et al., 2023; Leão et al., 2023):

$$\text{RR}_{(x)} = e^{\beta (X - X_0)} \quad (1)$$

$$N_{\text{assigned}} = [(\text{RR} - 1)/\text{RR}] \times N_{\text{total}} \quad (2)$$

Where,

RR = relative risk

X = average annual concentration of the pollutants (total mortality)

X_0 = cut-off or counterfactual concentration below which no quantification of the health impact is considered

β = risk coefficient resulting from a meta-analysis of epidemiological studies reported in AirQ+ software

N_{assigned} = number of total deaths assigned to the pollutants

N_{total} = total number of total deaths

The statistical coefficient β is unitless and varies depending on the health impact functions employed in each investigation. It is determined from epidemiological analysis to quantify the relationship between a negative health outcome (e.g., mortality) and the air pollution concentration (Yang et al., 2019). In our study: for $\text{PM}_{2.5}$ – mortality, all (natural)

causes – $\beta = 0.008$; mortality, cardiovascular – $\beta = 0.010$; mortality, respiratory – $\beta = 0.009$; for PM₁₀ – mortality, all (natural) causes – $\beta = 0.004$; mortality, IHD – $\beta = 0.006$; mortality, respiratory – $\beta = 0.011$; and for O₃ – mortality, all (natural) causes – $\beta = 0.0009$ and mortality, respiratory – $\beta = 0.002$.

To quantify the long-term effects of exposure to the three selected pollutants, we used the 24-hour average values for PM_{2.5} and PM₁₀ and the 8-hour average values for O₃ for the whole year and their average values after the simulations of temperature increase. We did not have missing values in the air pollution data sets. The size of the study area, the total population, the population at risk, the mortality rate per 100,000 inhabitants, and the cut-off limit concentration were also included as input data to the software. The AirQ+ software already included default values for relative risk (RR) (Wikuats et al., 2023). Optional input data also included latitude, longitude, and location identifiers. We assessed several health-related outcomes using this software tool as proposed by Arregocés et al. (2023), including the attributable proportion of cases, number of attributable cases, number of attributable cases per 100,000 at-risk population, proportion of cases in the pollutant concentration range, and cumulative distribution by air pollutant concentration.

3. Results

The descriptive analysis of the three pollutant concentrations can be seen in Table 1. The annual average for fine particulate matter exceeded the values recommended by the WHO throughout 2022, while this value was within the range considered safe for ozone and remained very close to the recommended guideline for coarse particulate matter. However, the measured values for PM₁₀ exceeded the daily limit values proposed for 2021 on 22 occasions (6.02%), and for PM_{2.5} it happened on 64 occasions (17.53%). As for O₃ levels in daily 8-hour measurements, concentrations were only above the limit values on 5 days (1.36%).

Table 1

Descriptive analysis of PM_{2.5}, PM₁₀, and O₃ levels in Sinop/MT, Brazil, in 2022.

Pollutant (µg/m ³)	Annual mean (SD)	Median	Minimum	Maximum
PM _{2.5} (daily average)	10.79 (9.40)	7.30	1.72	83.26
PM ₁₀ (daily average)	15.01 (11.07)	10.37	2.46	188.00
O ₃ (daily 8 h max)	46.27 (20.87)	45.16	12.28	110.22

Table 2 shows the descriptive analysis of the meteorological parameters observed in the studied area, in 2022. Sinop experienced high temperatures throughout the year, with an average temperature above 26 °C. Despite the fluctuations observed, the average humidity for the year 2022 can be considered reasonable, as it is within the comfort zone. As for the UV radiation index, the annual average can be classified as “very high”, while the annual rainfall was within what is expected for cities belonging to the transition zone of the Amazon biome.

Table 2

Statistical summary of weather data in Sinop/MT, Brazil, in 2022.

Weather parameter	Mean $\pm$ SD	Minimum	Maximum	Total
Average temperature (°C)	26.51 $\pm$ 2.28	18.00	33.00	-
Minimum temperature (°C)	19.85 $\pm$ 2.20	10.00	24.00	-
Maximum temperature (°C)	33.15 $\pm$ 4.00	23.00	44.00	-
Wind speed (km/h)	9.01 $\pm$ 2.61	5.00	18.00	-
Humidity (%)	60.03 $\pm$ 19.13	23.00	97.00	-
Atmospheric pressure (hPa)	1013.02 $\pm$ 2.15	1005.40	1020.00	-
UV radiation index	8.57 $\pm$ 1.95	3.00	11.00	-
Precipitation (mm)	-	-	-	1855.20

The association between pollutants and meteorological variables can be observed through the Pearson correlation matrix described in Table 3. Temperature, humidity, atmospheric pressure, and UV radiation index were parameters that correlated with all three pollutants analyzed. Individually, O₃ showed significant correlations (whether positive or negative) with all meteorological parameters, while PM_{2.5} and PM₁₀ showed no correlation with wind speed or precipitation.

Table 4 presents the behavior of air pollutants based on simulation scenarios for a temperature increase (by adding 0.5 °C each time) from +0.5 °C to +4 °C. In terms of PM_{2.5}, the 0.5 °C increase resulted in a concentration of 10.31 µg/m³, which is lower than the real values observed for 2022, which is why we did not use this result for the AirQ+ HIA simulations. However, it should be noted that the increase of +4 °C boosted PM_{2.5} levels by almost 47%. The scenarios for PM₁₀ also showed increased concentrations of this pollutant because of the temperature increase, ranging from 6.59% (+0.5 °C) to 67.55% (+4 °C). For this pollutant, all concentrations were used in the HIA simulations as they were above the observed and cut-off values. For O₃, even considering the progressive increase shown in Table 4, ozone

concentrations did not exceed the cut-off value ($60 \mu\text{g}/\text{m}^3$) until the $+2.5^\circ\text{C}$ mark was reached, thus limiting the test scenarios for the HIA. Nevertheless, in the most alarmist scenario, the O_3 values increased by more than 55 %.

The health effects of long-term exposure to $\text{PM}_{2.5}$, PM_{10} , and O_3 concentrations in 2022, determined using the AirQ+ modeling software, are shown in Tables 5–7. When analyzing the results obtained, it is observed that the increase in the number of deaths (indifferently the endpoint) is directly proportional to the increase in pollutant concentrations resulting from the scenarios of progressive increase in ambient temperature. Concerning $\text{PM}_{2.5}$, it should be noted that at the levels verified in 2022, the municipality of Sinop has already recorded deaths attributable to this pollutant (all natural causes), taking into account that the annual average of this pollutant was more than double the level recommended in the new AQGs for 2021. In the worst-case scenario of a temperature increase ($+4^\circ\text{C}$), the number of deaths attributable to $\text{PM}_{2.5}$ almost doubles compared to the baseline, both for all natural causes of death and for cardiovascular mortality. The lowest numbers of deaths attributable to this pollutant were observed for respiratory mortality.

Regarding PM_{10} , the number of deaths attributable to non-external causes under the conditions observed in 2022 was only one case, since the concentration of this pollutant remained practically within the limit proposed by WHO. However, if we look at the values predicted for scenarios with a greater temperature increase, the number of attributable deaths rises rapidly. Mortality from IHD in Sinop proved to be unrepresentative, which is probably due to the low number of reported cases. As for respiratory mortality, no cases were verified under baseline conditions, but with the increase in temperature, they also began to occur, faster than the cases predicted for ischemic diseases.

For ozone, deaths from natural causes were also limited to one case in 2022. From a temperature rise of 3°C , on the other hand, the number of deaths began to increase significantly and reached 15 times the number of cases recorded for 2022 at a temperature rise of 4°C . Exclusively for respiratory deaths from ozone (Table 7), only at increases of 3.5°C and 4°C did the attributable proportion (AP %), the estimated number of attributable cases (NAC) and the estimated number of attributable cases per 100,000 population at risk (NACPR), simultaneously deviate from 0 %/0 cases, so that the other values (60.47 and 64.35), although above the cut-off limit, were disregarded for the analysis.

4. Discussion

This is the first study to assess the health effects of three major air pollutants in the city of Sinop, in the north of the state of Mato Grosso. What is also new is that we have introduced temperature as a weather variable that can influence pollutant concentrations in simulated scenarios demonstrating that climate change can have a direct impact on people's lives in the area. Even though, other research groups have already studied the relationship between health outcomes and air pollution in other Mato Grosso cities or adjacent states, including the Amazon, Cerrado, and Pantanal biomes (Ignotti et al., 2007; Ignotti et al., 2010; Silva et al., 2010; Pereira et al., 2011; Carmo and Hacon, 2013; Silva et al., 2016). Those authors highlighted, for example, the contribution of wildfires and climatic features to increases in pollutant levels. Many of these works were produced, however, in the first decade of the 21st century.

Regarding the pollutant levels in Sinop, the annual average for PM_{2.5} determined in our study is quite similar to the value of 9.1 µg/m³ determined by Gonçalves et al. (2023) for the entire state of Mato Grosso (average of 141 municipalities). It should be noted that PM_{2.5} exceeded the values proposed by the WHO most frequently when compared to O₃ and PM₁₀. In light of this, it is important to clarify that the methodology used by CAMS to provide its data differs from that proposed by the WHO for determining pollutant levels and developing its guidelines. Nevertheless, CAMS data are increasingly being used for such analyses in air pollution studies in countries such as Brazil, which have few air monitoring stations over a vast area, as in the study proposed by Roux et al. (2020).

The results of the meteorological parameters for the year 2022 can be compared with the time series developed by Mota et al. (2013), who analyzed the data of the water and climate balance of Sinop between 1972 and 2010. In this sense, the precipitation for 2022 is close to the average of the 38-year time series, which was 1947 mm. However, the average humidity decreased by 18.4 percentage points, while the values for minimum, average, and maximum temperatures were also above the historical average. Leite-Filho et al. (2021) highlighted that increasing deforestation in the region is one of the main drivers of this hydrological imbalance. Although our results are isolated, they indicate a phenomenon of climate change in progress in Amazonian communities that has already been verified in other studies (B. Oliveira et al., 2021; Carauta et al., 2021).

Humidity and temperature had the strongest correlation with O₃, PM₁₀, and PM_{2.5}, among the weather variables analyzed. The intimate relationship between meteorological variables and atmospheric pollution is still little explored, especially outside large cities. Many of the studies on climate change are focused on carbon dioxide (CO₂) and other greenhouse

gases, while recent studies have demonstrated that particulate matter can also absorb and emit thermal radiation, possibly contributing to the generation of heat (Chen et al., 2021).

One of the possible explanations for the negative correlation between humidity and ozone could be the increase of hydroxyl radicals in the atmosphere when humidity is reduced, a process that favors the formation of ground-level O₃ (Awang et al., 2018). In terms of particulate matter, studies suggest that with increased humidity, the particles may undergo a washout/deposition process that is favored by humidity and leads to a decrease in particulate matter concentration (Nguyen et al., 2016).

Our results also showed a positive correlation between atmospheric pressure and particulate matter, but a negative one with ozone. Other studies have found that atmospheric pressure is a parameter that correlates positively with O₃ (Souza et al., 2018) and PM (Tian et al., 2014) concentrations. One of the reasons for this is that increasing atmospheric pressure tends to maintain stable meteorological conditions, which can hinder the dispersion of pollutants (Samad et al., 2020). The negative correlation observed in Sinop has already been pointed out in other studies (Xueping et al., 2019; Ilic et al., 2020), and according to Toh et al. (2013), it is still not entirely clear whether there is a causality between air pressure and ozone.

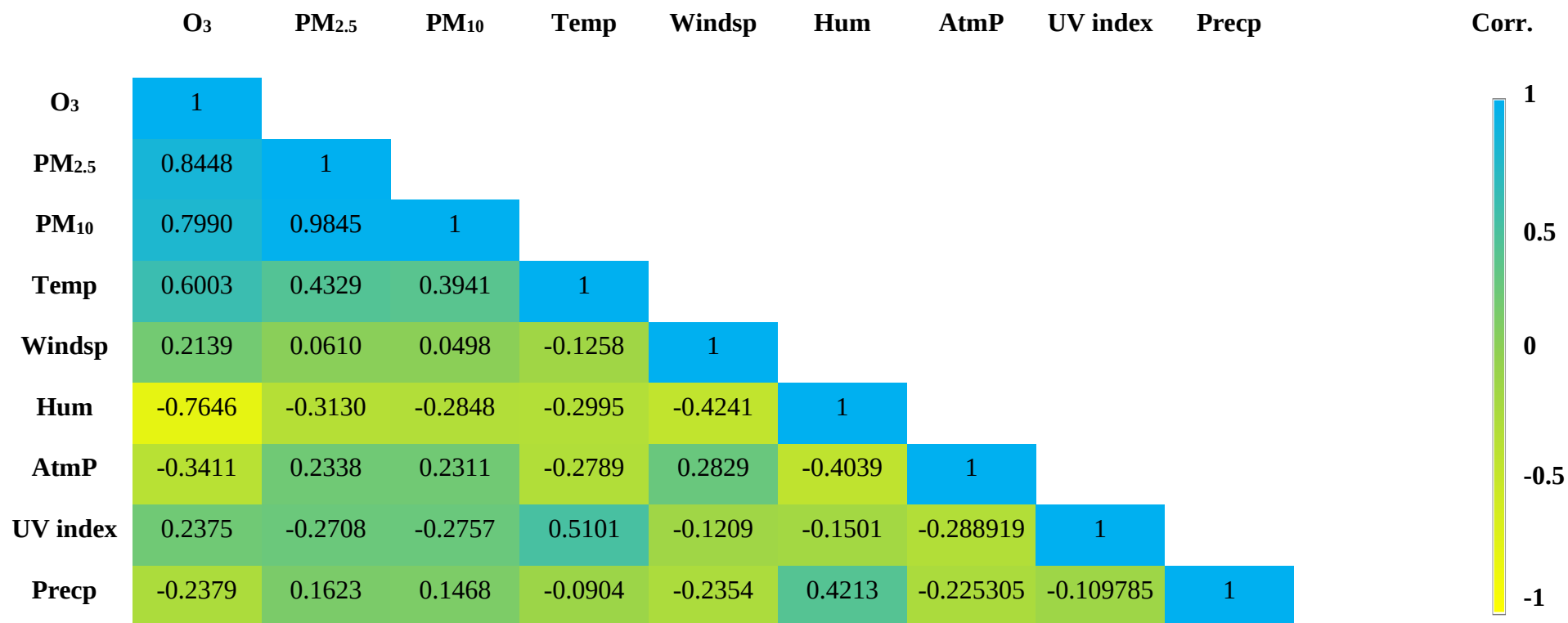
The effects that have been demonstrated concerning the UV index are better established, as solar radiation plays an important role in the photochemical processes that lead to the formation of O₃ in the troposphere (Jasaitis et al., 2016). Other studies also suggest that the presence of particulate matter in the atmosphere can lower UV index values (Kermani et al., 2020).

Particulate matter and ozone are sensitive to climate change, especially temperature increase (Kalisa et al., 2018; Kinney, 2021). Temperature plays an important role in the formation and persistence of ground-level ozone in the atmosphere, even when airborne precursors are reduced (Dewan and Lakhani, 2022). For the same reason, and due to regional differences, the levels of particulate matter can rise sharply during periods of increased temperature, especially in regions with prolonged drought (Kalisa et al., 2018; Sant'Anna and Rocha, 2020; Brum et al., 2024).

For particulate matter, this can occur due to greater turbulence, atmospheric instability, and enhanced vertical and horizontal movement of particles (Munir et al., 2017). Increased volatilization of compounds that participate in the formation of particulate matter also occurs on hotter days (Bolan et al., 2024). Furthermore, the drier conditions caused by the increase in temperature also favor the occurrence of fires, closely linked to the formation of particulate matter. Previous studies also have shown that the risk of death after exposure to O₃ and PM₁₀

482 **Table 3**

483 Pearson correlation matrix of air pollutants and weather parameters in Sinop/MT, Brazil, in 2022.



484 Temp – temperature; Windsp – wind speed; Hum – humidity; AtmP – atmospheric pressure; Precp – precipitation. Red color indicates
 485 $p < 0.05$.

486

487 **Table 4**
488 Summary of air pollutant levels (mean ± SD) in simulated temperature increase scenarios (from +0.5 °C to +4 °C) in Sinop/MT, Brazil,
489 in 2022.

Pollutant (µg/m³)	Observed	+0.5 °C	+1.0 °C	+1.5 °C	+2.0 °C	+2.5 °C	+3.0 °C	+3.5 °C	+4.0 °C
PM _{2.5} (daily average)	10.79 (9.40)	10.31 (3.60)	10.99 (3.81)	11.73 (4.00)	12.48 (4.19)	13.28 (4.03)	14.11 (4.51)	14.97 (4.66)	15.86 (4.81)
PM ₁₀ (daily average)	15.01 (11.07)	16.00 (5.58)	17.07 (6.02)	18.21 (6.45)	19.45 (6.87)	20.76 (7.27)	22.17 (7.64)	23.62 (8.01)	25.15 (8.36)
O ₃ (daily 8 h max)	46.27 (20.87)	45.91 (18.23)	49.31 (19.24)	52.91 (20.10)	56.63 (20.72)	60.47 (21.15)	64.35 (21.36)	68.24 (21.38)	72.10 (21.17)

490

491

492 **Table 5**493 Health effects attributed to long-term exposure to different PM_{2.5} levels (observed + predictions after temperature increase)

Health endpoint	ICD 10	Age	At-risk population	Annual incidence ^a	Exposure	Cut-off value (µg/m ³)	Annual mean (µg/m ³) ^b	RR ^c	AP (%)	NAC	NACPR
Non-external mortality	A00 - R99	>30	98527 ^d	312	PM _{2.5}	5	10.79		4.36 (3.32 - 4.87)	13 (10 - 15)	13.60 (10.35 - 15.19)
							10.99		4.51 (3.43 - 5.03)	14 (11 - 15)	14.06 (10.70 - 15.70)
							11.73		5.04 (3.84 - 5.63)	15 (12 - 17)	15.73 (11.98 - 17.56)
							12.48	1.08 (1.06	5.59 (4.26 - 6.24)	17 (13 - 19)	17.45 (13.31 - 19.48)
							13.28	- 1.09)	6.17 (4.71 - 6.89)	19 (14 - 21)	19.26 (14.70 - 21.49)
							14.11		6.77 (5.17 - 7.55)	21 (16 - 23)	21.13 (16.13 - 23.56)
							14.97		7.39 (5.64 - 8.23)	23 (17 - 25)	23.04 (17.61 - 25.69)
							15.86		8.02 (6.13 - 8.93)	25 (19 - 27)	25.02 (19.13 - 27.88)

Cardiovascular mortality	I00 - I99	>30	98527	89	PM _{2.5}	5	10.79	5.86 (4.87 - 7.31)	5 (4 - 6)	5.22 (4.33 - 6.50)	
							10.99	6.06 (5.03 - 7.55)	5 (4 - 7)	5.39 (4.48 - 6.72)	
							11.73	6.77 (5.63 - 8.43)	6 (5 - 7)	6.03 (5.01 - 7.50)	
							12.48	1.11 (1.09 - 1.14)	7.51 (6.24 - 9.34)	7 (5 - 8)	6.68 (5.56 - 8.31)
							13.28	8.28 (6.89 - 10.28)	7 (6 - 9)	7.37 (6.13 - 9.15)	
							14.11	9.07 (7.55 - 11.25)	8 (7 - 10)	8.07 (6.72 - 10.01)	
							14.97	9.88 (8.23 - 12.25)	9 (7 - 11)	8.79 (7.33 - 10.90)	
Respiratory mortality	J00 - J99	>30	98527	38	PM _{2.5}	5	15.86	10.71 (8.93 - 13.26)	9 (8 - 12)	9.54 (7.95 - 11.80)	
							10.79	1.10 (1.03 - 1.18)	5.37 (1.70 - 9.14)	2 (1 - 3)	2.04 (0.64 - 3.47)
							10.99	5.55 (1.75 - 9.44)	2 (1 - 4)	2.11 (0.67 - 3.59)	

11.73	6.20 (1.97 - 10.53)	2 (1 - 4)	2.36 (0.75 - 4.00)
12.48	6.88 (2.19 - 11.64)	3 (1 - 4)	2.61 (0.83 - 4.43)
13.28	7.59 (2.42 - 12.81)	3 (1 - 5)	2.88 (0.92 - 4.87)
14.11	8.32 (2.66 - 14.00)	3 (1 - 5)	3.16 (1.01 - 5.32)
14.97	9.06 (2.90 - 15.21)	3 (1 - 6)	3.44 (1.10 - 5.78)
15.86	9.83 (3.16 - 16.45)	4 (1 - 6)	3.74 (1.20 - 6.25)

494 AP – Estimated Attributable Proportion. NAC – Estimated number of Attributable Cases (Excess cases). NACPR - Estimated number
 495 of Attributable Cases per 100,000 Population at Risk. ^aPer 100,000 people. ^bObserved mean and means after temperature increase.
 496 ^cRelative risk (RR) with its 95% confidence interval for a threshold value of 5 µg/m³, estimated by the log-linear model. ^dNumber of
 497 people in Sinop over 30 years old according to IBGE (2022).

498

499 **Table 6**500 Health effects attributed to long-term exposure to different PM₁₀ levels (observed + predictions after temperature increase)

Health endpoint	ICD 10	Age	At-risk population	Annual incidence	Exposure	Cut-off value (µg/m ³)	Annual mean (µg/m ³) ^a	RR ^b	AP (%)	NAC	NACPR
Non- external mortality	A00 - R99	>30	98527	312	PM ₁₀	15	15.01	1.04 (1.03 - 1.06)	0.37 (0.28 - 0.55)	1 (1 - 2)	1.16 (0.87 - 1.72)
							16.00		0.40 (0.30 - 0.59)	1 (1 - 2)	1.23 (0.93 - 1.83)
							17.07		0.81 (0.61 - 1.20)	2 (2 - 4)	2.52 (1.90 - 3.74)
							18.21		1.25 (0.95 - 1.86)	4 (3 - 6)	3.92 (2.96 - 5.80)
							19.45		1.73 (1.31 - 2.56)	5 (4 - 8)	5.40 (4.08 - 7.99)
							20.76		2.24 (1.69 - 3.31)	7 (5 - 10)	6.98 (5.28 - 10.32)
							22.17		2.77 (2.09 - 4.09)	9 (6 - 13)	8.64 (6.53 - 12.75)
							23.62		3.33 (2.52 - 4.90)	10 (8 - 15)	10.38 (7.86 - 15.30)

Ischemic heart disease mortality	I20 - I25	>30	98527	24	PM ₁₀	15	25.15	3.91 (2.96 - 5.75)	12 (9 - 18)	12.19 (9.23 - 17.93)	
							15.01	0.55 (0.09 - 0.90)	0	0.13 (0.02 - 0.22)	
							19.45	2.56 (0.44 - 4.15)	1 (0 - 1)	0.61 (0.11 - 1.00)	
							20.76	3.31 (0.57 - 5.35)	1 (0 - 1)	0.79 (0.14 - 1.28)	
							22.17	1.06 (1.01 - 1.10)	4.09 (0.71 - 6.60)	1 (0 - 2)	0.98 (0.17 - 1.58)
							23.62	4.90 (0.86 - 7.90)	1 (0 - 2)	1.18 (0.21 - 1.90)	
							25.15	5.75 (1.01 - 9.23)	1 (0 - 2)	1.38 (0.24 - 2.22)	
Respiratory mortality	J00 - J99	>30	98527	38	PM ₁₀	15	15.01	1.07 (0.55 - 1.64)	0	0.41 (0.21 - 0.62)	
							17.07	1.12 (1.06 - 1.19)	2.32 (.12 - 3.54)	1 (0 - 1)	0.88 (0.46 - 1.34)
							18.21	3.58 (1.86 - 5.45)	1 (1 - 2)	1.36 (0.71 - 2.07)	

19.45	4.92 (2.56 - 7.45)	2 (1 - 3)	1.87 (0.97 - 2.83)
20.76	6.33 (3.31 - 9.55)	2 (1 - 4)	2.41 (1.26 - 3.63)
22.17	7.79 (4.09 - 11.71)	3 (2 - 4)	2.96 (1.55 - 4.45)
23.62	9.32 (4.90 - 13.94)	3 (2 - 5)	3.54 (1.86 - 5.30)
25.15	10.88 (5.75 - 16.20)	4 (2 - 6)	4.13 (2.18 - 6.16)

501 AP – Estimated Attributable Proportion. NAC – Estimated number of Attributable Cases (Excess cases). NACPR - Estimated number
502 of Attributable Cases per 100,000 Population at Risk. ^aObserved mean and means after temperature increase. ^bRelative risk (RR) with
503 its 95% confidence interval for a threshold value of 15 µg/m³, estimated by the log-linear model.

504

505 **Table 7**506 Health effects attributed to long-term exposure to different O₃ levels (observed + predictions after temperature increase).

Health endpoint	ICD 10	Age	At-risk population	Annual incidence	Exposure	Cut-off value (µg/m ³)	Annual mean (µg/m ³) ^a	RR ^b	AP (%)	NAC	NACPR
Non-external mortality	A00 - R99	All ages ^c	200000 ^d	627	PM ₁₀	60	60.47		0.05 (0 - 0.09)	1 (0 - 1)	0.29 (0.00 - 0.58)
							64.35	1.01 (1.00 - 1.02)	0.43 (0 - 0.86)	5 (0 - 11)	2.71 (0.00 - 5.38)
							68.24		0.82 (0 - 1.62)	10 (0 - 20)	5.12 (0.00 - 10.15)
							72.10		1.2 (0 - 2.37)	15 (0 - 30)	7.50 (0.00 - 14.85)
							68.24	1.02 (1.00 - 1.05)	1.62 (0 - 3.94)	1 (0 - 1)	0.62 (0.00 - 1.50)
Respiratory mortality	J00 - J99	>30	98527	38	PM ₁₀	60	72.10		2.37 (0 - 5.73)	1 (0 - 2)	0.90 (0.00 - 2.18)

507 AP – Estimated Attributable Proportion. NAC – Estimated number of Attributable Cases (Excess cases). NACPR - Estimated number
508 of Attributable Cases per 100,000 Population at Risk. ^aObserved mean and means after temperature increase. ^bRelative risk (RR) with
509 its 95% confidence interval for a threshold value of 60 µg/m³, estimated by the log-linear model. ^cIncidence includes individuals of all
510 ages. ^dTotal population in Sinop – MT, Brazil.

may be higher in summer (Pascal et al., 2021). Moreover, heat waves and outdoor air pollution are linked, and their synergistic effects are expected to lead to severe consequences in the future (Grigorieva and Lukyanets, 2021). Interestingly, our study showed a stronger correlation between temperature and PM_{10} than with $PM_{2.5}$. this type of behavior is not linear between studies and can be explained in part by the fact that higher temperature tends to result in higher energy consumption, which in turn results in changes in local pollution, including components in particulate matter that vary by location. Such alterations in PM composition make them more or less susceptible to responding to temperature variations (Buckley et al., 2014; Kavouras and Chalbot, 2017).

In our study, simulations of temperature increase from 0.5 to 4.0 °C resulted in significant variations in the assessed pollutant levels. These changes indicate that the air quality in Sinop may deteriorate due to the progressive increase in ambient temperature. This finding is important considering that the global average temperature in 2022 was already 1.15 °C above the 1850-1900 average (United Nations, 2023). The use of ML techniques for studies predicting the concentrations of air pollutants in different scenarios has increased and the results presented are convincing as this tool facilitates the work with multiple data and the analysis of complex phenomena such as the interaction between meteorological variables and pollutants, as in the study developed by Zhou et al. (2022). In addition, Samad et al. (2023) emphasize that it is possible to derive great benefits from ML strategies by creating virtual monitoring stations for air quality and air pollution, reducing the cost and dependence on physical monitoring stations that limit the scope of collecting and analyzing these data.

Although the fluctuations in pollutant levels were notable, these increases could be even more significant as our model did not consider the increase in wildfires, which are a notable consequence of the temperature rise in the region. Sinop is located in a fire-prone area, both due to the anthropogenic activities prevalent in the region and its climatic characteristics, and its air quality has already been shown to be quite vulnerable to the effects of biomass burning (Moura et al., 2024). Other consequences not considered in the model concern the progressive increase in energy demand that Brazil will face due to the rise in temperature and droughts, which may overload Brazil's main energy source, hydropower. Today, hydroelectric plants generate more than 60% of the electricity consumed in Brazil (Cuartas et al., 2022). One of the direct consequences of this critical scenario could be the increased use of coal or other fossil fuels to the detriment of cleaner and more sustainable energies (Bezerra et al., 2021), directly contributing to increased air pollution.

In terms of long-term health effects, non-external mortality (all natural causes) was higher for PM_{2.5}, with a concentration of 15.86 µg/m³, more than 8% of attributable deaths would be associated with exposure to this pollutant, almost doubling the number of premature deaths (excess cases) when comparing the results with the baseline quantified in 2022 (10.79 µg/m³). It is interesting to note that the population over 30 years in Sinop is very close to 100,000 people, so the NAC (excess cases) and NACPR values are usually similar.

Also, for cardiovascular and respiratory mortality due to PM_{2.5} pollution, the proportion of attributable deaths increased progressively with the increase in pollutant concentration. Although this seems to be an obvious result, the number of outcomes may be quite different. For example, Matkovic et al. (2020), when examining the health-protective effects of reducing PM_{2.5} pollution on the population of two cities in Bosnia and Herzegovina, found that the benefits of reducing air pollution may not directly translate into health benefits over time, particularly due to the variety of factors involved in increasing or decreasing mortality that cannot be accounted for by the models.

Nevertheless, Thangavel et al. (2022) mentioned that several studies confirm the finding that elevated PM_{2.5} concentrations contribute more to disease and mortality than other pollutants, mainly due to the smaller size of the particles, which have a high permeability in the body (Bouchriti et al., 2023). Recent investigations have shown that prolonged exposure to high levels of PM_{2.5} increases the risk of various health problems (Nawaz and Henze, 2020; Yu et al., 2022).

Concerning respiratory mortality, exposure to higher levels of PM₁₀ would account for a greater attributable proportion, although the number of premature deaths would be the same as for PM_{2.5}. As with O₃, the number of attributable deaths for non-external mortality was found to be greater than that of PM₁₀. For this pollutant, however, the results for respiratory diseases were not paramount. This result might have been different if critical O₃ values had been considered instead of annual averages, for example on days when wildfires occurred, given the influence this phenomenon has on tropospheric ozone concentrations and health outcomes (Silva et al., 2016; Moura et al., 2024).

Exposure to PM₁₀ and ground-level ozone is known to contribute to the development of various diseases, of which cardiorespiratory diseases are the most common. Wikuats et al. (2023) also highlighted that the known effects of PM_{2.5} can be aggravated by simultaneous exposure to O₃ and can even favor the occurrence of potentially dangerous respiratory infections in risk groups such as children, the elderly, pregnant women, and people with chronic diseases (Pamplona et al., 2020).

Scientific findings have confirmed that the rise in temperature itself is already associated with various health consequences. Ebi et al. (2021) emphasized that heat waves are associated with an excessive number of deaths, even in countries with a high level of development and greater resilience. Work absenteeism, dehydration, higher hospitalization rates, higher mortality rates from cardiorespiratory diseases and heat stroke, adverse birth and pregnancy outcomes, mental illness, and higher healthcare costs are other consequences already linked to hot weather (Cheng et al., 2019; Liss and Naumova, 2019; Chersich et al., 2020; Cianconi et al., 2020; Orlov et al., 2020).

This perception may indicate that the increase in temperature associated with the increase in air pollutant concentrations could contribute to health consequences that were not yet observed in the baseline levels collected for 2022. It is very relevant for an expanding municipality such as Sinop, which is undergoing intense changes, attracting a larger population, and thus facing new challenges related to urbanization and industrialization (Coy et al., 2022). It is important to emphasize that our predictions of a rise of up to 4° C are not immediate scenarios but are in line with studies developed since the beginning of the 21st century that already pointed to a similar and progressive temperature rise in South America by 2100 (Boulanger et al., 2006).

Although our results are limited to a single municipality and a period of only one year, they call for strategies to mitigate these effects. Health problems and premature mortality cause high costs to the public health system and affect countries' income generation and development (Fuller et al., 2022). Initiatives such as the development of public policies to control and monitor air quality have already been presented as useful means to minimize these impacts (De Moura and Da Silva Júnior, 2023a). However, the search for clean and technological strategies such as improvements in public and individual transportation, sustainable buildings, and the expansion of knowledge about the risks associated with pollution are also fundamental and urgent processes (Piracha and Chaudhary, 2022).

In addition, recent studies have pointed to other resources that can be used to reduce the inaccuracies found when working with satellite data on air pollution, such as the use of geostationary satellites instead of polar-orbiting satellites (O'Dell et al., 2023). This type of action can facilitate and accelerate comprehension and mass communication about the drastic deterioration of air quality in certain regions in the face of extreme events (volcanoes, major fires, toxic spills), so that measures can be taken to reduce the exposure and disease rate of the populations.

Some limitations of the present study must be acknowledged. First, as this is an ecological study, it is impossible to adequately control or account for various specificities or confounding variables. Second, the AirQ+ software does not consider scenarios involving multiple exposures or associations with multiple pollutants, and it relies on ambient data as a proxy for population exposure. Third, estimating pollution data without local monitoring stations as validation sources can lead to inaccuracies. Finally, the use of data obtained over only one year represents a weakness for more reliable predictions. However, other studies have already shown valid results using a short time window (C. Liu et al., 2021; Yang et al., 2021; Yang et al., 2022; Xu et al., 2023).

This study also has its strengths. Despite the short period of analysis, by using an integrated and robust methodology, it was possible to predict the impacts of climate change and air pollution in a rapidly developing city located in one of the world's most important regions in this context, the Amazon rainforest. In addition, compared to previous works, we were able to demonstrate the probable consequences of such changes on human health, a problem that may have been underestimated until now. It also provides a basis for the development of similar investigations in other cities in the Midwest and North of Brazil, where air pollution is widespread, but its effects are less recognized than in the Southeast region.

5. Conclusion

In conclusion, this study sheds light on the relationship between air quality, climate change, and public health in the city of Sinop, Brazil. Our results highlight the worrying levels of particulate matter and ozone observed in 2022, with PM_{2.5} levels frequently exceeding WHO guidelines. The correlations observed between meteorological variables and pollutant levels underline the significant influence of climate factors on air quality dynamics. Simulations of temperature increase scenarios indicate a potential worsening of air pollution in Sinop, especially in terms of PM_{2.5} and PM₁₀ concentrations. The health impact assessment revealed a burden of premature mortality associated with long-term exposure to these pollutants. These findings underline the urgency of implementing effective mitigation strategies by authorities and stakeholders. Therefore, the need for comprehensive air quality monitoring and targeted public health measures to mitigate the negative health impacts of air pollution in rapidly developing cities is compelling.

CRedit authorship contribution statement

Fernando Rafael de Moura: Methodology, Formal analysis, Writing – Original Draft, Writing – Review & Editing; **Romina Buffarini:** Formal analysis, Writing – Review & Editing; **Edison Luis Devos Barlem:** Writing – Review & Editing; **Willian César Nadaleti:** Writing – Review & Editing; **Helotonio de Carvalho:** Writing – Review & Editing; **Flávio Manoel Rodrigues da Silva Júnior:** Conceptualization, Methodology, Software, Formal analysis, Resources, Writing – Review & Editing, Supervision.

Declaration of competing interest

The authors declare that they do not have any known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data availability

Data will be made available by the corresponding author upon reasonable request.

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7. CONCLUSÕES

A poluição atmosférica tornou-se um dos maiores desafios a serem enfrentados pela humanidade na busca por um processo de desenvolvimento que seja sustentável a longo prazo. Por ser ubíqua interage com os ecossistemas provocando diversos tipos de alterações, impactando desde os parâmetros meteorológicos até a biodiversidade. Igualmente, ao afetar todos os seres humanos expostos a ela, os impacta em diferentes níveis a depender de diversas questões que perpassam desde suas doenças pregressas, até a condição social em que estão inseridos.

Nesse sentido, este estudo buscou contribuir com novas percepções de questões ligadas à poluição do ar. Em seu primeiro manuscrito, discutimos como a poluição atmosférica e as mudanças climáticas se apresentam como obstáculos diretos ao alcance das metas propostas pelos Objetivos do Desenvolvimento Sustentável da Agenda 2030. A partir desse pano de fundo, avançamos para o segundo manuscrito que abordou diretamente a cidade de Sinop, Mato Grosso, município fortemente marcado pelo crescimento do agronegócio e localizado na vulnerável região do ecótono Cerrado-Amazônia. Neste segundo estudo analisamos a química dos poluentes em relação aos frequentes episódios de incêndios florestais que ocorrem no município. Num terceiro momento, o último manuscrito trouxe uma investigação sobre a interação entre o aumento de temperatura e as concentrações dos poluentes atmosféricos e como essa dinâmica pode influenciar em desfechos de saúde da população sinopense.

Mais do que chamar a atenção para uma problemática já conhecida, pretendemos que nossos trabalhos forneçam subsídios para fortalecer o desenvolvimento de novas ações que culminem com um monitoramento amplo e eficiente da qualidade do ar, que é ainda tão deficitário fora do eixo Sudeste-Sul no Brasil. Além disso, ao abordarmos a questão da poluição do ar a partir de um prisma diferente daquele empregado por boa parte dos estudos que já foram desenvolvidos no Centro-Oeste e, por extensão, no Brasil, acreditamos ter contribuído com respostas para perguntas importantes na consolidação dessa temática e para uma melhor compreensão da relação meio ambiente x saúde.

Nossos achados também apontam para a necessidade de mais estudos sobre a realidade das pequenas e médias cidades, cujos níveis de poluição podem até superar o das grandes metrópoles e que, no entanto, dispõem de menos recursos de enfrentamento. Dessa forma, ao falarmos de ações de mitigação, podemos explorar três eixos: a) locais afetados por poluição oriunda da queima de biomassa; b) centros urbanos e a poluição oriunda de fontes móveis

(carros, ônibus, caminhões) e c) regiões industriais, cujas principais fontes de emissões são fixas.

No caso dos incêndios, alterações da cobertura vegetal original e desconhecimento da dinâmica do fogo favorecem a ocorrência de episódios críticos. Assim sendo, alternativas ligadas à divulgação científica e à educação ambiental podem auxiliar no enfrentamento desse desafio, aumentando a percepção social sobre o tema, seja por esclarecer de que maneiras as pessoas podem contribuir para a ocorrência de menos incêndios, como também estratégias para prevenção em saúde quando eles já estiverem deflagrados.

Já no que concerne às fontes móveis, o incentivo a um transporte público eficiente e barato, pode contribuir para uma redução significativa das frotas veiculares em circulação diária. Da mesma forma, a opção por meios de transporte menos poluentes como bicicletas e metrô, também contribuem para esse intento, embora exijam investimentos de infraestrutura urbana. Quantos aos veículos elétricos, embora úteis para o controle de poluição do ar, levantam uma discussão diferente que está justamente na capacidade de países em desenvolvimento sustentarem essa transição de matriz energética de forma bem estruturada.

As fontes fixas, bastante problemáticas em grandes centros urbanos, igualmente podem impactar regiões menos desenvolvidas pelo descolamento da poluição provocado pelos eventos meteorológicos. Mais do que mudanças nas fontes de recursos e meios de produção, a aplicação mais incisiva do “princípio do poluidor-pagador”, atribuindo a obrigação do poluidor (pessoa, empresa) em arcar com os custos da reparação do dano causado ao meio ambiente por ele, pode ser uma solução imediata para este eixo, enquanto outras estratégias de médio e longo prazo sejam planejadas e operacionalizadas.

Isto posto, para promover uma melhor qualidade de vida, através da melhoria da qualidade do ar, é essencial que os atores envolvidos estejam conscientes e adotem uma abordagem mais crítica. Isso requer uma mudança tanto na “mentalidade” das empresas privadas, quanto na postura dos órgãos ambientais e dos tomadores de decisão. É fundamental que o foco das políticas públicas seja voltado para a proteção da saúde humana sob uma ótica integral, levando em conta os pressupostos da Saúde Única, que nos mostra que o bem-estar humano está intimamente conectado ao bem-estar dos outros seres vivos e dos ecossistemas.