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PROGRAMA DE PÓS-GRADUAÇÃO EM CIÊNCIAS DA SAÚDE

POTENCIAIS IMPACTOS CAUSADOS POR POLUENTES ATMOSFÉRICOS À SAÚDE DA POPULAÇÃO RESIDENTE EM REGIÃO COM ATIVIDADES DE EXPLORAÇÃO E QUEIMA DE CARVÃO

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Tese apresentada ao Programa de Pós Graduação em Ciências da Saúde da Universidade Federal do Rio Grande, como requisito parcial à obtenção do título de Doutor em Ciências da Saúde.

Orientador: Prof. Dr. Flavio Manoel Rodrigues da Silva Júnior

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Banca Examinadora

Anna Maria Siebel – FURG

Julia Oliveira Penteado – UFPEL

Bruna Marmett – UFCSPA

Orientador: Flavio Manoel Rodrigues da Silva Júnior

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SUMÁRIO

RESUMO

A poluição atmosférica ocorre por meio da liberação de substâncias químicas para o meio ambiente, podendo tornar o ar impróprio ou nocivo à saúde humana. Em algumas regiões do planeta, as atividades de mineração são responsáveis por grande parte da emissão destes poluentes. A exposição da população aos poluentes advindos da atividade de mineração pode acarretar em efeitos nocivos à saúde, como doenças alérgicas, respiratórias e cardiovasculares, tendo em vista que a exposição humana a substâncias químicas pode ocorrer principalmente através da via de exposição inalatória. O objetivo deste estudo foi avaliar o risco à saúde humana decorrente da exposição à poluição atmosférica e os potenciais benefícios da redução da concentração dos poluentes do ar na maior jazida de carvão mineral do país, localizada no município de Candiota – RS. Sendo assim, o estudo foi conduzido em duas etapas: na primeira, foi avaliado o impacto na saúde ocasionado pela exposição à poluição do ar com base na estimativa de mortes atribuíveis ao PM_{10} e $PM_{2,5}$ e os potenciais benefícios em mortalidade, internações hospitalares, expectativa de vida e custos, sendo simulados em dois cenários distintos. O primeiro cenário foi a diminuição dos valores médios dos poluentes em $5\mu g/m^3$ e, no segundo, foi considerada a redução dos níveis dos poluentes dentro dos valores máximos permitidos na Legislação Brasileira. Na segunda etapa foi realizada a avaliação de risco à saúde humana decorrente da exposição aos poluentes atmosféricos NO_2 e SO_2 e metais ligados ao PM_{10}, ademais, foi avaliado a correlação dos parâmetros meteorológicos para a dinâmica e risco potencial dos poluentes ligados ao PM_{10} no município de Candiota. Os resultados obtidos na primeira etapa do estudo mostraram que com a redução do $PM_{2,5}$ nos dois cenários avaliados, o número de mortes evitadas é condizente com o aumento na expectativa de vida, gerando um benefício monetário médio de mais de 33 milhões de dólares. Esses dados se assemelham com os resultados obtidos na redução do PM_{10} nos dois cenários, indicando uma diminuição de internações e mortes o que resultaria em um benefício monetário de mais de 5 milhões de dólares por internações respiratórias e cardíacas e mais de 6 milhões em mortalidade por causas não externas. Na segunda etapa, os resultados mostraram ausência de risco à saúde humana decorrente da inalação de metais ligados ao PM_{10} bem como para os gases NO_2 e SO_2. O Pb foi metal que apresentou as maiores concentrações no PM_{10} seguido por Ni, As, Se e Cd respectivamente. Pode-se observar que nenhum dos poluentes atmosféricos avaliados ultrapassaram os valores máximos permitidos pela Legislação no Brasil. A associação dos poluentes do ar com os dados meteorológicos mostra que a temperatura apresentou correlação negativa com a maioria dos metais avaliados. Observou-se também que o teor dos metais ao longo do ano foi influenciado pelos meses do ano, onde o Pb e o Cd tiveram suas maiores concentrações nos meses de inverno. Assim, pode-se concluir que as atividades de mineração e queima de carvão na região de Candiota liberam para a atmosfera poluentes potencialmente nocivos à saúde. Logo, é importante ressaltar que, ainda que os poluentes avaliados não demonstrarem risco para a saúde através da exposição inalatória, os efeitos aditivos de diversos poluentes e vias de exposição não devem ser negligenciados. Contudo, ressalta-se que a diminuição da concentração dos poluentes na área de estudo traz benefícios tanto na saúde e qualidade de vida da população exposta quanto benefícios monetários ao sistema único de saúde.

Palavras chave: poluição atmosférica, áreas de mineração, risco à saúde humana.

ABSTRACT

Atmospheric pollution occurs through the release of chemical substances into the environment, which can make the air inappropriate or harmful to human health. In some regions of the planet, mining activities are responsible for a large part of the emission of these pollutants. Exposure of the population to pollutants arising from mining activity can lead to harmful health effects, such as allergic, respiratory and cardiovascular diseases, considering that human exposure to chemical substances can occur mainly through inhalation exposure. The objective of this study was to evaluate the risk to human health resulting from exposure to atmospheric pollution and the potential benefits of reducing the concentration of air pollutants in the largest mineral coal deposit in the country, located in the municipality of Candiota - RS. Therefore, the study was conducted in two stages: in the first, the impact on health caused by exposure to air pollution was evaluated based on the estimate of deaths attributable to PM_{10} and $PM_{2.5}$ and the potential benefits in terms of mortality, hospital admissions, life expectancy and costs, being simulated in two different scenarios. The first scenario was the decrease in the average values of pollutants by 5μg/m^3 and, in the second, the reduction of pollutant levels within the maximum values allowed in Brazilian legislation was considered. In the second stage, an assessment of the risk to human health resulting from exposure to atmospheric pollutants NO_2 and SO_2 and metals linked to PM_{10} was carried out, in addition, the correlation of meteorological parameters to the dynamics and potential risk of pollutants linked to PM_{10} in the municipality of Candidate. The results obtained in the first stage of the study showed that with the reduction of $PM_{2.5}$ in the two scenarios evaluated, the number of deaths avoided is consistent with the increase in life expectancy, generating an average monetary benefit of more than 33 million dollars. These data are similar to the results obtained in the reduction of PM_{10} in both scenarios, indicating a decrease in hospitalizations and deaths, which would result in a monetary benefit of more than 5 million dollars for respiratory and cardiac hospitalizations and more than 6 million in mortality from non-external causes. In the second stage, the results showed no risk to human health from inhaling metals linked to PM_{10} as well as NO_2 and SO_2 gases. Pb was the metal that showed the highest concentrations in PM10 followed by Ni, As, Se and Cd respectively. It can be observed that none of the evaluated atmospheric pollutants exceeded the maximum values allowed by the legislation in Brazil. The association of air pollutants with meteorological data shows that temperature was negatively correlated with most of the evaluated metals. It was also observed that the metal content throughout the year was influenced by the months of the year, where Pb and Cd had their highest concentrations in the winter months. Thus, it can be concluded that mining and coal burning activities in the Candiota region release pollutants potentially harmful to health into the atmosphere. Therefore, it is important to emphasize that, even if the evaluated pollutants do not demonstrate a risk to health through inhalation exposure, the additive effects of different pollutants and exposure routes should not be neglected. However, it is noteworthy that the decrease in the concentration of pollutants in the study area brings benefits both to the health and quality of life of the exposed population and monetary benefits to the unified health system.

Keywords: atmospheric pollution, mining areas, risk to human health.

1. INTRODUÇÃO

Segundo a Organização das Nações Unidas (2017) o aumento populacional vem crescendo com o passar dos anos, podendo passar de 7,6 bilhões de pessoas em 2017 para 9,8 bilhões de pessoas em 2050. Já o crescimento populacional no Brasil passou de aproximadamente 194 milhões de pessoas no ano de 2010 para mais de 214 milhões de pessoas em 2022, sendo projetado que no ano de 2050 a população total seja de aproximadamente 232 milhões de pessoas (IBGE, 2022).

Com o aumento populacional e a alta demanda por recursos naturais e alimentos, consequentemente ocorreu o aumento de ações antropogênicas, as quais correspondem a ações exercidas pelo homem onde o ambiente sofre alterações podendo gerar impactos negativos como a poluição dos solos, rios, água subterrânea, mares e atmosfera (Bidone *et al*., 2018; Islam *et al*., 2018). Segundo a Organização Mundial da Saúde (OMS) (2022), a poluição atmosférica ocorre por meio da liberação de agentes químicos que modificam as características naturais da atmosfera. As principais fontes artificiais dos poluentes atmosféricos são combustão de combustível de veículos, processos industriais, refinaria de petróleo, queima de resíduos, dentre outros. Essas atividades, como por exemplo, a mineração, o processamento de recursos naturais, a queima de gás durante a produção de petróleo, são responsáveis pela liberação de toneladas de substâncias químicas nocivas liberadas para a atmosfera.

A Resolução do Conselho Nacional do Meio Ambiente (CONAMA) n° 491 de 2018, descreve os poluentes atmosféricos como qualquer forma de matéria em quantidade, concentração, tempo ou outras características que tornem ou possam tornar o ar impróprio ou nocivo à saúde. A poluição atmosférica é medida através da quantidade de substâncias químicas poluentes presentes no ar, podendo ser encontradas diversas substâncias tais como, compostos de enxofre, compostos de nitrogênio, compostos orgânicos, monóxido de carbono, compostos halogenados, metais, material particulado e oxidantes fotoquímicos (CETESB, 2021). Para a avaliação da qualidade do ar, deve ser levado em consideração o material particulado, que é um conjunto de poluentes constituídos de poeiras, fumaças e materiais sólidos e líquidos onde se mantém suspenso na atmosfera devido seu tamanho ser pequeno (CETESB, 2021) segundo os padrões para a qualidade do ar estipulados na Resolução CONAMA N. 491 de 19 de Novembro de 2018.

A exposição humana aos poluentes atmosféricos ocorre através das vias inalatória, contato dérmico, exposição ocular e oral, sendo que diversas variáveis podem influenciar a exposição, como por exemplo, fatores genéticos e fisiológicos (idade, sexo, condição física, doenças preexistentes) e fatores demográficos, físicos e sociais, tendo em vista que as variáveis ambientais interagem com os demais fatores podendo agir como facilitadores da exposição aos poluentes aumentando a probabilidade de gerar efeitos adversos à saúde humana (Gouveia, 2005).

Segundo a OMS (2016), cerca de 9 em cada 10 pessoas respiram ar contendo altos níveis de poluentes, sendo estimado um total de 7 milhões de mortes todos os anos através da exposição humana a partículas inaláveis finas, presentes em locais que apresentam poluição atmosférica, tanto em ambientes externos quanto internos. A poluição atmosférica já causou cerca de 4,2 milhões de mortes em 2016, tendo em vista que os países mais pobres e marginalizados estão propensos a maior exposição aos poluentes atmosféricos. A qualidade do ar urbano em 98% das cidades em países de baixa e média renda não atende às diretrizes da qualidade do ar da OMS, sendo que em países de alta renda essa porcentagem cai para 56%. Mais de 90% das mortes ocorrem em países de baixa e média renda, como por exemplo, na Ásia e África. Assim, a poluição do ar é considerada um fator de risco crítico para doenças crônicas não transmissíveis, causando cerca de 24% das mortes por doenças cardíacas, 25% por acidentes vasculares cerebrais, 43% por doenças pulmonares obstrutivas crônicas e 29% por câncer de pulmão (OMS, 2016).

As atividades de mineração de carvão são um importante recurso energético não renovável, sendo explorado em torno de todo o mundo. Entretanto essa exploração apresenta uma série de desvantagens quando relacionados aos processos sociais e ambientais, tendo em vista a liberação de poluentes que implicam negativamente a qualidade ambiental (Torrezani *et al*., 2013). Dentre estes poluentes pode-se destacar os metais, como o As, Cd, Pb, Zn, Ca, Fe, Mg e Ni, os quais podem ser encontrados em altas concentrações, muitas vezes próximos ou até mesmo superiores aos teores máximos permitidos na Legislação (Pires *et al*., 2001), sendo assim relacionados a uma série de efeitos adversos à saúde humana (Zhang *et al*., 2020; Briki *et al*., 2017). Diante do exposto, torna-se necessário a realização de estudos em áreas de mineração a fim de uma melhor compreensão do potencial risco à saúde humana exposta em áreas com influência de atividades de mineração.

2. REVISÃO BIBLIOGRÁFICA

2.1. Caracterização da atmosfera

A atmosfera é a estrutura gasosa da superfície terrestre, composta por cinco camadas chamadas de exosfera, termosfera, mesosfera, estratosfera e troposfera. A troposfera é a camada mais próxima da terra sendo essencial e indispensável para a vida dos organismos, fornecendo o oxigênio necessário para a respiração e atuando na manutenção do equilíbrio térmico do planeta. A atmosfera é composta por 78% de nitrogênio, 21% de oxigênio e 1% de dióxido de carbono, argônio, vapor de água, outros gases e partículas (Varejão-Silva, 2006).

Troposfera é a camada mais próxima da crosta terrestre. Nela encontra-se o ar usado na respiração de plantas e animais. A troposfera é a camada mais densa da atmosfera, onde está concentrada a maior parte dos gases. É nela que os poluentes atmosféricos se encontram (Branco, 2014).

Estratosfera é a segunda camada mais próxima da terra. Nela podemos encontrar o gás ozônio, sendo responsável pela barreira de proteção dos raios ultravioleta. A estratosfera apresenta pouco fluxo de ar podendo ser muito instável (Branco, 2014).

Mesosfera é a terceira camada da atmosfera, onde a temperatura diminui à medida que a altitude aumenta. Nessa camada as temperaturas podem chegar a -90°C, sendo considerada a mais fria entre as camadas da atmosfera (Branco, 2014).

Termosfera corresponde à camada intermediária entre a mesosfera e a exosfera, podendo ser chamada também de ionosfera, pois concentra uma grande quantidade de íons. O ar na termosfera é rarefeito, predominando o gás hidrogênio. Ao contrário da mesosfera a termosfera pode chegar a 1500°C em seu limite superior (Branco, 2014).

Exosfera é a última camada da atmosfera e apresenta a transição entre a atmosfera terrestre e o espaço sideral. Metade desta camada é composta por gás hélio e outra metade por hidrogênio. As temperaturas na exosfera podem superar os 1000°C (Branco, 2014).

2.2. Poluição atmosférica

Diante do aumento populacional e da alta demanda por recursos naturais e alimentos, a contaminação ambiental passou a ser um problema diário no mundo. Podendo ocorrer à contaminação da água, solo e atmosfera (Tirima *et al*., 2018; Zheng *et al*., 2019). Os poluentes atmosféricos podem ser classificados como primários sendo liberados diretamente das fontes de emissão como, por exemplo, óxidos de nitrogênio (NOx), amônia (NH_3), monóxido de carbono (CO) e metano (CH_4), ou secundários onde são formados na atmosfera através de reações químicas entre poluentes primários e componentes naturais da atmosfera como a água, dentre eles encontramos o peróxido de hidrogênio (H_2O_2), ácido sulfúrico (H_2SO_4), ácido nítrico (HNO_3) e trióxido de enxofre (SO_3) (Torres & Martins, 2005). Os poluentes atmosféricos podem ser provenientes de fontes naturais como as cinzas e gases de emissões vulcânicas e partículas e gases de incêndios florestais. Além disso, podem ser produzidos por meio artificial, através de ações antropogênicas, a partir da queima de combustíveis fósseis como o petróleo, gás natural e carvão mineral, sendo liberados através de fontes fixas ou móveis (Torres & Martins, 2005).

A poluição atmosférica é definida pela mudança da composição da atmosfera por meio da introdução de substâncias químicas no ar, podendo colocar em risco a qualidade de vida dos seres vivos (Amegah & Agyei-Mensah, 2017). Quando se refere à poluição atmosférica deve-se levar em consideração a composição química e concentrações das substâncias bem como fatores ambientais e climáticos, pois assim que o contaminante é lançado para a atmosfera irá sofrer ações de variáveis como velocidade e direção do vento, taxa de precipitação, temperatura, instabilidade do ar dentre outros fatores (Guerra & Miranda, 2011). Como mostra o estudo realizado por Liu *et al*. (2019), em que a qualidade do ar pode ser modificada de acordo com as condições climáticas. As substâncias químicas aderidas nas partículas do ar normalmente são carregadas pelas ações dos ventos, sendo que os níveis de poluentes no ar normalmente são superiores em áreas urbanas do que em áreas rurais, no entanto, estudos mostram que os poluentes podem migrar para áreas distantes de onde foram liberados (Miller Jr., 2007; Genga *et al*., 2018).

Dentre as principais fontes poluidoras da atmosfera é possível destacar os veículos automotores que são capazes de liberar monóxido de carbono (CO) e dióxido de carbono (CO_2) (Hudda & Fruin, 2018). Já as indústrias como, por exemplo, refinarias de petróleo, indústrias de fertilizantes, são responsáveis por grande parte da emissão de poluentes atmosféricos, dentre eles o dióxido de enxofre (SO_2), monóxido de carbono (CO), gás carbônico (CO_2) e óxidos de nitrogênio (NOx), no qual podem percorrer longas distâncias pelos ventos, transportando grandes quantidades de material particulado, que acabam afetando a saúde e a qualidade do ar (Da Silva Júnior *et al*., 2009). As Atividades industriais também estão relacionadas com a contaminação de metais liberados para o ambiente, como por exemplo, cobre, chumbo e zinco, que são encontrados em partículas inaláveis PM_{10} e $MP_{2,5}$ (Xue *et al*., 2018).

Para a avaliação da qualidade do ar no Brasil, deve-se levar em consideração a Resolução do CONAMA N. 491, de novembro de 2018, que dispõe os padrões para qualidade do ar. Segundo esta resolução o padrão de qualidade do ar é determinado como o valor de concentração de um poluente específico na atmosfera, associado a um intervalo de tempo de exposição, para que o meio ambiente e a saúde da população sejam preservados em relação aos riscos de danos causados pela poluição atmosférica. Os poluentes atmosféricos no qual devem ser avaliados são: material particulado PM_{10}, material particulado $MP_{2,5}$, dióxido de enxofre (SO_2), dióxido de nitrogênio (NO_2), ozônio (O_3), fumaça, monóxido de carbono (CO), partículas totais em suspensão (PTS) e o chumbo (medido nas partículas totais em suspensão).

2.3. Efeitos adversos da exposição humana à poluição atmosférica

Diversos estudos têm demonstrado que a inalação de substâncias químicas aderidas ao material particulado pela população acarreta em efeitos negativos para a saúde, podendo ocorrer danos como, doenças cardiovasculares (Zhang *et al.*, 2018, Khafaie *et al.*, 2016), doença alérgicas, respiratórias, imunológicas, neurológicas e até mesmo o câncer (Schraufnagel *et al.*, 2018).

O material particulado é classificado como: partículas totais em suspensão (PTS), cujo diâmetro aerodinâmico é menor ou igual a 50 µm; partículas inaláveis (PM_{10}), cujo diâmetro aerodinâmico é menor ou igual a 10 µm e partículas inaláveis finas ($PM_{2,5}$), cujo diâmetro aerodinâmico é menor ou igual a 2,5 µm (CONAMA, 2018). O tamanho das partículas está relacionado diretamente com o seu potencial de causar danos à saúde, sendo que as partículas entre 5 a 10 µm tentem a ficar retidas em vias aéreas extratorácicas, de 1 a 5 µm ficam retidas nas vias aéreas traqueobronquiais e as partículas menores que 1 µm conseguem alcançar os alvéolos no pulmão (Oberdörster *et al.*, 2005).

Estudos como os realizados por Ogino *et al*. (2019) e Yang *et al*. (2019) têm relatado os possíveis danos causados por partículas inaláveis $PM_{2,5}$. As substâncias químicas aderidas a estas partículas são nocivas para os seres vivos, podendo levar a lesões pulmonares, desequilíbrio imunológico, inflamação das vias aéreas superiores, dentre outros. Porém o que torna a poluição atmosférica ainda mais preocupante, além dos estudos relacionados com os danos causados pela poluição atmosférica, são os acidentes no mundo inteiro que levam a milhares de mortes por intoxicação através da inalação de substâncias químicas aderidas nas partículas totais em suspensão do ar. Como o caso chamado de “o grande nevoeiro de 1952”, onde aproximadamente 12 mil pessoas morreram e 150 mil pessoas ficaram hospitalizadas devido à inalação de dióxido de enxofre. Segundo a Organização Mundial da Saúde, a poluição do ar mata em torno de 7 milhões de pessoas por ano, a maioria em países pobres.

2.3.1. Perfis toxicológicos dos poluentes atmosféricos abordados no presente estudo

2.3.1.1. Partículas inaláveis (PM_{10}) e partículas inaláveis finas ($PM_{2,5}$)

As partículas inaláveis (PM_{10}) e as partículas inaláveis finas ($PM_{2,5}$) são compostas por um conjunto de poluentes constituídos por poeiras, fumaças, materiais sólidos e líquidos no qual se mantém suspensos na atmosfera devido seu tamanho ser muito pequeno (CETESB, 2023). Sendo assim, o material particulado em suspensão pode apresentar diferentes compostos químicos, como os íons SO_4^{2-}, HSO_4^{2-}, NO^{3-},NH^{4+}e H^+, fuligem, compostos orgânicos, cinzas, elementos traço, como por exemplo, Pb, Cd, Cr, Al, Fe, dentre outros (Brito *et al*., 2018). Dentre as principais fontes de emissão destes poluentes se destacam os veículos automotores, processos industriais, queima de biomassa e ressuspensão de poeira do solo (CETESB, 2023).

As partículas inaláveis (PM_{10}) são definidas por possuírem o diâmetro aerodinâmico menor ou igual que 10 µm, já as partículas inaláveis finas ($PM_{2,5}$) possuem o diâmetro aerodinâmico menor ou igual que 2,5 µm (CETESB, 2023). Assim, os potenciais efeitos adversos à saúde humana estão amplamente relacionados ao tamanho das partículas, tendo em vista que quanto menor o seu tamanho, mais profundamente será sua deposição no sistema respiratório e potencial impacto sobre a saúde (Brito *et al*., 2018).

A exposição humana ao PM_{10} e $PM_{2,5}$ pode ocorrer de forma aguda (durante um curto período), ou de forma crônica (ao decorrer de meses e anos). Dentre os principais efeitos adversos à saúde é possível destacar morbidade respiratória e cardiovascular, como por exemplo, agravamento da asma, problemas respiratórios, câncer de pulmão o que consequentemente irá levar ao aumento de internações hospitalares. Assim, pode-se observar que a exposição a curto prazo ao PM_{10} pode estar relacionado a uma série de problemas respiratórios, já a mortalidade é mais evidenciada através da exposição a longo prazo, sendo que o maior risco está relacionado ao $PM_{2,5}$. Deve-se levar em consideração que pessoas no qual possuem doenças pulmonares pré-existentes, bem como crianças e adultos, são considerados mais suscetíveis e vulneráveis aos efeitos adversos da exposição a estes poluentes. A exposição de crianças ao MP pode acarretar no desenvolvimento pulmonar prejudicado e insuficiência pulmonar crônica (OMS, 2013).

2.3.1.2. Arsênio

O arsênio é um metaloide no qual exibe propriedades metálicas e não metálicas, sendo que os estados de oxidação mais comuns são a forma trivalente e a pentavalente. Os compostos de arsênio podem ser classificados em compostos inorgânicos, compostos orgânicos de arsênio e gás arsina (ATSDR, 2007).

A absorção do arsênio inorgânico através dos pulmões depende de fatores, como por exemplo, sua forma química, tamanho das partículas e solubilidade. As partículas maiores, com mais de 10 µm de diâmetro aerodinâmico são depositadas principalmente nas vias aéreas superiores, enquanto que as partículas menores que 2 µm penetram nos alvéolos dos pulmões. Estima-se que a absorção total do arsênio pela via inalatória seja cerca de 30 a 35%, pelo trato gastrointestinal, estudos apontam que mais de 90% da dose ingerida é absorvido (WHO/EUROPE, 2000), já a via dérmica é a mais baixa, onde cerca de 2,8% é absorvido (ATSDR, 2007).

Após o arsênio ser absorvido é transportado pelo sangue para todo o corpo (ATSDR, 2007), podendo ser encontrado nos músculos, ossos, rins, pulmões, pele, unhas e cabelos. Os efeitos da valência e do nível de exposição na distribuição tecidual de arsênio indicam que os níveis nos rins, fígado, bile, cérebro, esqueleto, pele e sangue são de 2 a 25 vezes maiores para a forma trivalente do que a pentavalente (WHO/EUROPE, 2000). Dentre os principais efeitos adversos da exposição humana ao arsênio pode-se destacar o aumento do risco de câncer de pulmão, irritação respiratória, náusea, efeitos na pele, problemas neurológicos, alterações no sistema cardiovascular, dentre outros (ATSDR, 2007).

2.3.1.3. Cádmio

O cádmio é um metal componente da crosta terrestre, podendo ser encontrado associado aos minérios de zinco, cobre e chumbo. O cádmio pode se transformar no ambiente para a valência Cd+2, no qual pode ser solubilizado no organismo, sendo assim sua forma mais tóxica. O cádmio metálico pode ser solubilizado principalmente nos pulmões, sendo que a via inalatória é a principal via de exposição. Após a absorção, a biodisponibilidade do Cd+2 é considerada independente da fonte de cádmio com a qual houve exposição respiratória (EUROPEAN COMISSION, 2007).

Após a exposição inalatória, o tamanho da partícula bem como a solubilidade os fluídos biológicos são os fatores determinantes mais importantes para sua toxicocinética (ATSDR, 2012). As taxas de absorção do cádmio podem variar de aproximadamente 25% através da exposição pela via inalatória, de 1 a 10% através da exposição via oral e menos de 1% pela via dérmica (ATSDR, 2012).

Após a absorção, o cádmio é transportado pela corrente sanguínea até o fígado, onde induz a produção da metalotioneína no qual forma um complexo com esta proteína, assim sendo liberado do fígado para o sangue podendo ser transportado para os rins. Quando a capacidade de produzir o complexo proteína-metal é excedida, o cádmio pode se acumular nos túbulos renais onde irá causar danos às células tubulares (ECHA, 2017). O cádmio pode ser encontrado no organismo principalmente nos rins e fígado (Kemi, 2011).

Dentre os principais efeitos adversos à saúde através da exposição ao cádmio podem-se destacar efeitos respiratórios, como por exemplo, edema pulmonar, traqueobronquite, pneumonite; danos renais, como nefropatia e disfunção renal, dentre outros (ATSDR, 2012).

2.3.1.4. Selênio

O selênio pode ser encontrado naturalmente nos solos e nas rochas. Possui diferentes formas, como selenatos (VI), selenitos (IV), selenetos (II) e raramente são encontrados como elemento selênio (ATSDR, 2003). O selênio é um elemento essencial em humanos e animais, fazendo parte de diversas proteínas e enzimas responsáveis em mecanismos de defesa antioxidantes. Na literatura existem poucos estudos relacionados aos efeitos da toxicidade através da via inalatória, porém após a exposição aguda ao pó ou fumaça de selênio o órgão mais afetado é o pulmão, estando relacionado a efeitos adversos cardiovasculares, hepáticos, nervosos e renais (ATSDR, 2003).

No organismo o selênio pode ser encontrado no sangue, cabelo, unhas, leite materno, tendo em vista que as maiores concentrações são encontradas no fígado e rins. Sua eliminação pode ocorrer através da urina e das fezes, no qual irá depender do tempo de exposição e da forma em que foi ingerido. Quando ocorre a exposição aguda a concentrações tóxicas, o selênio ou seus compostos podem ser eliminados através da respiração (ATSDR, 2003).

Os principais efeitos adversos da exposição ao selênio estão relacionados à selenose, alterações endócrinas, danos no sistema respiratório, efeitos cardiovasculares, gastrointestinais, hematológicos, dentre outros (ATSDR, 2003).

2.3.1.5. Chumbo

O chumbo é um elemento de coloração cinca azulado que pode ser encontrado naturalmente em rochas e minerais. O chumbo pode ser utilizado na sua forma pura, sendo ela a metálica, ou em compostos químicos como os óxidos. O chumbo normalmente não é encontrado em seu estado natural, e sim em combinações a outros elementos. Deve-se ressaltar que a forma química dos metais como o chumbo, influencia na forma em que será absorvido (ATSDR, 2020).

O chumbo é uma substância tóxica responsável por causar danos a muitos órgãos e sistemas, no qual pode afetar diversas atividades biológicas. Independente da via de exposição seja ela inalatória ou oral, os efeitos biológicos são os mesmos. Após a absorção do chumbo através da via inalatória e oral, o chumbo não sofre metabolização ou biotransformação e complexa-se com diversas macromoléculas. Assim o chumbo é absorvido, distribuído e excretado na forma de complexo. O chumbo que não é absorvido pela via gastrointestinal é excretado através das fezes, enquanto que a absorvida é excretada pelos rins (ECHA, 2012).

O chumbo inorgânico após ingressar no organismo é distribuído para os tecidos moles, como por exemplo, rins, medula óssea, fígado e cérebro, bem como para os tecidos mineralizados, ossos e dentes. A principal via de exposição ao chumbo é através da via inalatória, onde após ser inalado é depositado no trato respiratório inferior onde é completamente absorvido (ECHA, 2012).

Os efeitos adversos do chumbo estão amplamente relacionados ao sistema nervoso central. Após a exposição de adultos ao chumbo, os efeitos neurológicos podem ocorrer em níveis sanguíneos relativamente baixos, podendo ser observado alterações comportamentais, fadiga e diminuição da capacidade de concentração. Já em crianças pode ser observado déficit cognitivo, déficit na escala de inteligência, processamento da fala e linguagem, atenção ou desempenho na escola e diminuição da acuidade auditiva (Mendes, 2003). Entretanto o chumbo está relacionado não somente aos efeitos neurológicos, mas também com alterações no sistema hematológico, danos gastrointestinais, alterações reprodutivas, dentre outros.

2.3.1.6. Níquel

O níquel pode ser encontrado naturalmente em rochas e minerais, sendo que dos diversos estados em que pode ser encontrado a forma +2 é a mais comum (ATSDR, 2005).

Após a exposição ao níquel através da via inalatória, as partículas de níquel são depositadas no trato respiratório superior e inferior no qual são absorvidas por diversos mecanismos. A deposição de níquel no trato respiratório está relacionada ao tamanho da partícula, tendo em vista que partículas entre 5-30 μm se depositam na área nasofaríngea por impactação inercial; 1-5 μm se depositam na região da traqueia e bronquiolar por sedimentação; e <1 μm se depositam na região alveolar dos pulmões onde ocorre difusão e precipitação eletrostática das partículas (ATSDR, 2005). A absorção do níquel no trato respiratório depende de fatores como a solubilidade dos seus compostos, tendo em vista que compostos solúveis são mais absorvidos que os compostos menos solúveis (ATSDR, 2005).

Após a exposição através da via inalatória, aproximadamente 35% no níquel é absorvido na corrente sanguínea, onde logo após é distribuído para os pulmões, rins e pele. Parte no níquel também pode permanecer na corrente sanguínea, bem como ser encontrado no cérebro, tecidos do estômago e intestino (HSDB, 2005). O mecanismo pelo qual o níquel causa efeitos adversos no trato respiratório pode estar relacionado com o acúmulo de macrófagos e material granular nos alvéolos bem como o aumento da densidade volumétrica de células alveolares tipo II (ATSDR, 2005). Dentre os principais efeitos adversos relacionados à exposição ao níquel podem-se destacar efeitos respiratórios, sensibilização cutânea, mutagenicidade e carcinogenicidade (ATSDR, 2005).

2.3.1.7. Dióxido de nitrogênio (NO_2)

O dióxido de nitrogênio (NO_2) é um gás no qual possui coloração marrom-avermelhada. Pode ser liberado para a atmosfera através de fontes naturais e antropogênicas, sendo resultado também da transformação do ácido nítrico em dióxido de nitrogênio. Os níveis desse poluente no ar podem variar de acordo com a hora do dia, estações do ano e fatores meteorológicos (WHO, 2000).

Tendo em vista que no ambiente o dióxido de nitrogênio é um gás, a única via de exposição que possui relevância para a exposição humana é através da via inalatória. Após a sua inalação, cerca de 70 a 90% podem ser absorvidos no trato respiratório, porém existem poucos dados presentes da literatura no qual descrevem a toxicocinética desta substância química (WHO, 2000).

Os efeitos adversos causados pela exposição ao dióxido de nitrogênio geralmente ocorrem em concentrações superiores a 1880 $\mu g/m^3$, entretanto essas concentrações raramente são encontradas no ar, assim os estudos têm focado em pessoas no qual possuem doenças pulmonares pré-existentes. Em pessoas que possuem doenças como, por exemplo, asma, doença pulmonar obstrutiva crônica, bronquite, após a exposição a baixos níveis de dióxido de nitrogênio pode ser observado decréscimos na capacidade vital forçada e volume expiratório em 1 segundo (FEV1) ou aumento na resistência das vias aéreas (WHO, 2000).

2.3.1.8. Dióxido de enxofre (SO_2)

O dióxido de enxofre (SO_2) é um gás incolor no qual é liberado para a atmosfera através de fontes naturais e ações antropogênicas. O dióxido de enxofre presente na atmosfera está relacionado à formação de chuvas ácidas, sendo também precursor dos sulfatos, que é um dos principais componentes do PM_{10} (CETESB, 2021).

Levando em consideração que o dióxido de enxofre é um gás, a principal via de exposição é através da via inalatória. Dentre os principais efeitos adversos da exposição humana a esse poluente pode-se destacar a dificuldade respiratória, alteração na defesa dos pulmões, agravamento de doenças respiratórias e cardiovasculares, tosse, falta de ar, chiado no peito, asma, dentre outros. Ressalta-se que pessoas que possuem doenças pulmonares pré-existentes, como asma, doenças crônicas de pulmão e coração e crianças são mais sensíveis aos efeitos da exposição ao dióxido de enxofre. Já os óxidos de enxofre ao agirem com outros compostos presentes no ar formam pequenas partículas que podem penetrar profundamente o pulmão, causando uma série de danos, como por exemplo, enfisema e bronquite (CETESB, 2021).

2.4. Atividades de mineração de carvão e seus impactos na saúde

Diversos estudos mostram que áreas com atividades de mineração são responsáveis por liberar para o meio ambiente substâncias químicas, como por exemplo, os metais, no qual podem contaminar diferentes matrizes ambientais, como o solo, a água e o ar. Sabe-se que o aumento destas substâncias tanto em áreas de mineração quanto em seu entorno pode causar efeitos nocivos para a saúde humana (Xie *et al*., 2017, Zhang *et al*., 2020; Briki *et al*., 2017).

No Brasil, a maior jazida de carvão mineral está localizada no município de Candiota no Rio Grande do Sul, extremo Sul do Brasil, concentrando cerca de 40% das reservas nacionais de carvão mineral. Candiota também possui uma usina termoelétrica a carvão no qual sua matéria-prima é proveniente das atividades de mineração da região (ANEEL, 2008).

Assim, Candiota bem como diversos municípios que são influenciados pelas atividades carboníferas, como Bagé, Pinheiro Machado, Hulha Negra, Aceguá e Pedras Altas, vem sendo foco de estudos ambientais e avaliação de risco à saúde humana potencialmente exposta. O estudo realizado por dos Santos *et al*. (2018), avaliou a presença de elementos traço (Pb, Cd, Mn, Cu, Zn e Se) em amostras de urina de crianças sob influencia das atividades de mineração de Candiota, sendo possível observar que os elementos Zn e Se apresentaram concentrações acima dos valores de referência. Este achado torna-se de grande imporancia, tendo em vista que as crianças podem ser mais vulneráveis que os adultos quando expostas a substâncias químicas, devido ao fato de ainda estarem em desenvolvimento.

Já o estudo realizado por Bonifácio *et al*. (2021), estimou a dose diária crônica e o índice de risco não carcinogênico para os elementos traço As, Cd, Ni, Pb e Se bem como para os ânions F^- e NO^{3-} em águas superficiais da região de Candiota. Assim, foi possível observar que todos os metais e ânions estavam dentro dos níveis máximos permitidos na Legislação Brasileira, exceto o Pb. Entretanto nenhum dos metais e ânions apresentaram HI maior que 1, porém a somatória dos valores de HI ficou próxima a 1, sendo que a maior contribuição para o risco total estava relacionada ao Pb e F^-.

Outro estudo realizado por Müller *et al*. (2021), avaliou o risco à saúde humana exposta ao As através das vias de exposição oral, dérmica e inalatória, em uma região sob a influência de deposição atmosférica da usina de Candiota, sendo avaliado a contribuição do solo e do MP_{10}. Quando avaliado separadamente as vias de exposição ar e solo não apresentaram riscos não carcinogênicos e carcinogênicos, entretanto quando considerado a somatória das vias de exposição avaliadas pode-se observar riscos carcinogênicos em áreas de até 9,4 km de distância da usina, mesmo em concentrações de As abaixo dos limites de segurança.

Diversos outros estudos também já foram realizados na área de Candiota, a fim de avaliar o potencial risco à saúde humana mostrando assim resultados negativos para a população exposta (Pinto *et al*., 2017; dos Santos *et al*., 2021; Bigliardi *et al*., 2021; Dupont-Soares *et al*., 2021). Apesar disso, mais estudos são necessários para compreender e explicar possíveis lacunas existentes aos potenciais riscos para a saúde humana exposta em áreas de mineração, sobretudo em Candiota.

2.5. Avaliação de risco à saúde humana

As substâncias químicas podem ser liberadas para o meio ambiente de forma artificial podendo gerar alterações das características naturais do solo, dos sedimentos, da água subterrânea e superficial e também do ar, gerando assim impactos negativos e riscos à saúde humana, meio ambiente e segurança e ordem pública. Sendo assim a avaliação de risco à saúde humana é um processo qualitativo e/ou quantitativo para determinar as chances de ocorrência de efeitos adversos à saúde, decorrentes da exposição humana a áreas contaminadas por substâncias perigosas. O risco carcinogênico é caracterizado pela probabilidade adicional de ocorrência de câncer em função de um evento de exposição associado a uma contaminação ambiental, considerando as substâncias químicas e o caminho de exposição avaliado. Já o risco não carcinogênico é o quociente de ocorrência que expressa a potencial ocorrência de efeitos adversos não carcinogênicos à saúde humana, considerando as substâncias químicas e o caminho de exposição (ATSDR, 2005; US.EPA, 1989).

Estudos de avaliação de risco correspondem à probabilidade da ocorrência adicional de efeitos adversos à saúde em um ser humano exposto a uma ou mais substâncias químicas presentes em uma área contaminada por meio de um, ou mais, cenário(s) de exposição. Essa avaliação permite estimar os danos carcinogênicos e não carcinogênicos para diferentes fontes de exposição, dentre elas, via inalatória, oral e dérmica, através da avaliação do índice de perigo (HI) e risco carcinogênico (CR). Quando O HI < 1 indica que o risco de efeitos não carcinogênicos não é proeminente, já quando HI > 1 indica um efeito não carcinogênico consideravelmente alto. O CR aceitável ou tolerável é de 1 x 10-6 a 1 x 10-4 (Cheng *et al*., 2018; Xu et al., 2019). Para realizar a avaliação de risco à saúde humana devem ser realizadas quatro etapas, dentre elas a coleta de dados, avaliação da exposição, avaliação da toxicidade e por fim a caracterização do potencial risco (US.EPA, 1989).

O presente estudo possui como foco a avaliação de risco à saúde humana através da via de exposição inalatória, sendo assim os modelos matemáticos devem ser calculados conforme as recomendações da US.EPA (2009):

$$EC\ (\mu g/m^3) = \frac{CA \times EF \times ET \times ED}{AT}$$

Onde:

EC = é a concentração de exposição (ug/m³);

CA = é a concentração do contaminante no ar (ug/m^3);
EF = é a frequência de exposição (dias/ano);
ET = é o tempo de exposição (24h/dia);
ED = é a duração da exposição (anos);
AT = tempo médio não carcinogênico é a duração da exposição (anos) x 365 dias (dias/anos) x 24h/dia. AT carcinogênico é 70 anos x 365 dias (dias/ano).

Já o cálculo do quociente de risco inalatório é:

$$HQ = \frac{EC\ (\mu g/m^3)}{RfC\ (mg/m^3)\ \times\ 1000 \mu g/mg}$$

Onde:

HQ = é o risco não carcinogênico da exposição a um determinado elemento;
RfC = é a concentração de inalação de referência mg/m^3-dia.

Se o HQ for maior que 1, acredita-se que o risco de efeitos não carcinogênicos não seja proeminente. Se o HQ for maior que 1, indica um efeito não carcinogênico consideravelmente alto.

O risco de inalação do ar deve ser calculado através da seguinte fórmula:

$$Risk = \mathrm{IUR}(\mu g/m^3)\ \times\ EC(\mu g/m^3)$$

Onde:

IUR = é o risco unitário de inalação. Sendo que o risco aceitável ou tolerável é de 1x10 a $1x10^{-4}$.

2.6. Avaliação dos impactos à saúde humana exposta ao material particulado

Segundo a OMS (2013) a poluição atmosférica representa um risco potencial tanto para o meio ambiente quanto para a saúde humana. Levando em consideração os estudos realizados, em grande maioria pelos estados da União Europeia, relacionados ao monitoramento do PM_{10} em áreas urbanas e suburbanas, aproximadamente 83% da população, das quais existem dados, está exposta ao PM_{10} que excedem as diretrizes para a qualidade do ar.

A exposição humana ao PM_{10} e $PM_{2,5}$ está relacionada a uma série de efeitos adversos como morbidade respiratória e cardiovascular, agravamento de doenças, aumento de internações hospitalares, sendo estimado que diariamente a mortalidade aumenta em 0,2-0,6% por 10 $\mu g/m^3$ de PM_{10}. Já a exposição crônica ao $PM_{2,5}$ está sendo associada ao aumento do risco mortalidade cardiopulmonar em 6-13% por 10 $\mu g/m^3$ de $PM_{2,5}$. Porém, ainda é incerto que exista um nível seguro para a exposição humana (OMS, 2013).

Assim, é estimado que 3% das mortes por câncer cardiopulmonar e 5% das mortes por câncer de pulmão podem ser atribuídas ao material particulado. Deste modo, pode-se dizer que a redução dos poluentes atmosféricos poderia gerar um aumento na expectativa de vida da população exposta, bem como uma série de benefícios e melhorias na qualidade de vida (OMS, 2013).

A fim de estimar a relação entre os níveis de poluentes atmosféricos e os desfechos na saúde, como a mortalidade, internações hospitalares, aumento na expectativa de vida, a metodologia descrita como “Health Impact Assessment” têm sido amplamente utilizada em todo o mundo (OMS, 2015). Diante disso, o presente estudo buscou estimar os impactos a curto e longo prazo para a população exposta ao PM_{10} e $PM_{2,5}$, segundo a metodologia descrita por Pascal *et al*. (2013), a estimativa de mortes relacionadas à poluição do ar conforme Ostro (2004), e por fim a avaliação econômica dos gastos com internações por problemas respiratórios e circulatórios de acordo com Abe & Miraglia (2016).

3. OBJETIVOS

3.1. Objetivo geral

Avaliar o risco à saúde humana frente à exposição à poluição atmosférica na maior jazida de carvão mineral do país, localizada no município de Candiota, no estado do Rio Grande do Sul, extremo Sul do Brasil, bem como os benefícios potenciais da redução dos poluentes do ar nesta região.

3.2. Objetivos específicos

Estimar a mortalidade atribuída ao material particulado, bem como os benefícios em indicadores de saúde associados à redução da poluição do ar aos limites estabelecidos pela Legislação local e pela OMS.

Realizar a avaliação de risco à saúde humana dos poluentes atmosféricos NO_2 e SO_2 e metais ligados ao PM_{10} no município de Candiota;

Avaliar a correlação dos parâmetros meteorológicos para a dinâmica e risco potencial dos poluentes atmosféricos NO_2 e SO_2 e metais ligados ao PM_{10}.

4. METODOLOGIA

As descrições detalhadas dos métodos utilizados neste estudo estão descritas nos artigos: "*Health Impact Assessment of Air Pollution in na area of the largest coal mine in Brazil"* e "*Human Health Risk Assessment of Air Pollutants in the Largest Coal Mining Area in Brazil"*, apresentados na seção resultados do presente estudo.

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5. RESULTADOS

5.1. ARTIGO 1

Health Impact Assessment of Air Pollution in an area of the largest coal mine in Brazil

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Health Impact Assessment of Air Pollution in an area of the largest coal mine in Brazil

Laiz Coutelle Honscha[1], Julia Oliveira Penteado[1], Valério de Sá Gama[1], Alícia da Silva Bonifácio[1], Priscila Aikawa[1], Marina dos Santos[1], Paulo Roberto Martins Baisch[1], Ana Luíza Muccillo-Baisch[1], Flavio Manoel Rodrigues da Silva Júnior[1]*

[1] Universidade Federal do Rio Grande - FURG, Avenida Itália, km 8 Campus Carreiros, Rio Grande, Rio Grande do Sul – Brazil - CEP 96203-900

*corresponding author – f.m.r.silvajunior@gmail.com +55 53 32935249

Abstract

Coal exploration and burning activities are among the activities with the greatest potential to cause atmospheric pollution due to the combustion process of this mineral and the consequent release of particles that, in significant quantities, can pose a potential health risk, mainly respiratory and cardiovascular diseases. The Candiota region, in the extreme south of Brazil, concentrates 40% of the national reserves of mineral coal and its burning is capable of releasing air pollutants, including particulate matter (PM). Some environmental and epidemiological studies have been carried out in the region, but so far there is no investigation to estimate the impact of PM on health outcomes. The current study aimed to estimate the mortality attributed to the PM, as well as the benefits in health indicators associated with the reduction of air pollution to the limits set forth in local legislation and WHO. Daily data on PM levels collected from an air quality monitoring station over a year were used, as well as population data and health indicators from 7 cities influenced by mining activities, such as total mortality and cardiovascular diseases and hospitalizations for cardiac and respiratory problems. In a scenario where PM levels are within legal limits, a percentage greater than 11% of cardiovascular deaths was attributed to pollution by $PM_{2.5}$ and the reduction in PM_{10} and $PM_{2.5}$ levels may be responsible for the increase in the expectation of life in up to 17 months and monetary gains of more than $ 24 million, due to the reduction in hospitalizations and mortality. Studies of this nature should be important tools made available to decision makers, with a view to improving environmental laws and a consequent improvement in the quality of life and health indicators of the population.

Keywords: Candiota, particulate matter, health services

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests

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Authors' contributions

LCH, JOP and VSG were responsible for writing the article, analyzing and interpreting the data. ASB and PRRMB were responsible for extracting the data from the databases and preparing the spreadsheets. MS, PA and ALMB helped to formulate the key research question and to correct the text. FMRSJ was the advisor and responsible for the research.

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Introduction

The World Health Organization (WHO) estimates that approximately seven million deaths worldwide are due to air pollution and that nine out of ten people breathe polluted air (WHO 2021). Poor air quality is one of the most important environmental factors in many major cities in the world, as it can cause a wide range of acute and chronic diseases, including impaired lung function and systemic inflammation (EPA, 2021; Gao et al. 2020), different types from cancers (EPA, 2021; Hwang et al. 2020, Turner et al. 2020), cardiac ischemia (Kim et al. 2021), chronic obstructive pulmonary disease, myocardial infarction and stroke (Chen et al. 2020; Lee et al. 2018; Niu et al. 2021).

Air pollution is composed of a mixture of gases and particles, among which we highlight the gases ozone, sulfur dioxide, nitrogen dioxide, carbon monoxide and particulate matter (PM) (CONAMA 2018). PM is a complex mixture of solid and liquid particles suspended in the air, of natural or anthropogenic origin, which have a chemical composition of inorganic ions (sulfates, nitrates, ammonium, sodium, potassium, calcium, magnesium and chloride) and, organic, (hydrocarbons of various chemical classes) in addition to metals such as (cadmium, copper, nickel vanadium and zinc) (Cheung et al. 2013; Cavalcante et al. 2017; Guo et al. 2020). The PM is classified according to its diameter in PM_{10} inhalable particles with aerodynamic diameter less than 10 µm, and $PM_{2.5}$, ultra-fine inhalable particles with aerodynamic diameter less than 2.5 µm (USEPA 2021).

Since 2013, the International Agency for Research on Cancer (IARC) has included Atmospheric Particulate Matter within the group of carcinogenic substances (IARC, 2021). In general, studies point to negative health effects due to exposure to $PM_{2.5}$ and PM_{10}, (Alemayehu et al. 2020; Liu et al. 2021), as a higher risk of cardiac arrhythmia, stroke, acute myocardial infarction, lung disease, asthma and cancer (Hayes et al. 2019; Qibin et al. 2020; Chen et al., 2021).

A meta-analysis carried out with 19 cohort studies pointed out that the 10 $\mu g/m^3$ increase in $PM_{2.5}$ levels is responsible for the 6 to 11% increase in lung cancer mortality (Cui et al. 2015). However, such studies are still expensive and difficult to implement and methodologies of lower cost and complexity, as mathematical models validated by international agencies, are highlighted and can help in predicting health impacts.

The methodology called "Health Impact Assessment" has been widely used to estimate the relationship between levels of air pollutants and health outcomes, such as mortality and hospital admissions (WHO 2015). Studies around the world have used this methodology and revealed that scenarios with decreased levels of air pollutants are able to reduce mortality, hospitalizations and economic costs and increase the life expectancy of the population (Naddafi et al 2012, Abe & Miraglia 2016, Bayat et al. 2019).

In the extreme south of Brazil, the Candiota region has been the subject of environmental health studies because it is an important area for the exploration and burning of coal. The Candiota mine concentrates 40% of the national reserves of mineral coal (ANEEL 2008), which is the raw material for a coal-fired power plant with a capacity greater than 700 MW. In the region, numerous epidemiological studies have pointed out negative effects resulting from human exposure to the activities of coal mining and its pollutants (Pinto et al 2017, Da Silva Júnior et al 2018, Dos Santos et al. 2018, Bigliardi et al. 2021). However, there are no data on the mortality attributed to air pollution in the region, nor are there studies that estimate the health benefits related to the reduction of air pollution in the region. The evaluation of this scenario is useful, since PM_{10} and $PM_{2.5}$ concentrations may be elevated in coal burning area (Aneja et al 2012, Roy et al 2019).

Thus, the present study aimed to assess the health impact of air pollution in the largest coal mining region in the country, based on the estimation of deaths attributable to PM_{10} and $PM_{2.5}$, as well as the potential benefits on mortality, hospital admissions, life expectancy and economic costs in two simulated scenarios to improve the levels of these pollutants.

Material and methods

Study area

The study was conducted with data from 7 municipalities in a coal mining and burning region in Rio Grande do Sul, Brazil (Figure 1). The municipality of Candiota, home to coal mining activities, has approximately 8,771 inhabitants and is located approximately 420 km from the state capital, Porto Alegre. Also included were 6 municipalities that are considered to be influenced by coal activities: Bagé, has approximately 117 thousand inhabitants and 64.9 km away from Candiota, Pinheiro Machado 12,780 inhabitants and 46.4 km away from Candiota, Herval 6,753 inhabitants and with 93.9 km distance from Candiota, Hulha Negra 6,043 inhabitants and 39.6 km in relation to Candiota, Aceguá 4,394 inhabitants and 120km distance from Candiota, finally Pedras Altas 2,212 inhabitants and 20.35km distance from Candiota (Brazil, 2010), totaling an impacted population of 157,953 thousand inhabitants. The economy of these locations is based on agriculture and the extraction and industrial exploitation of minerals.

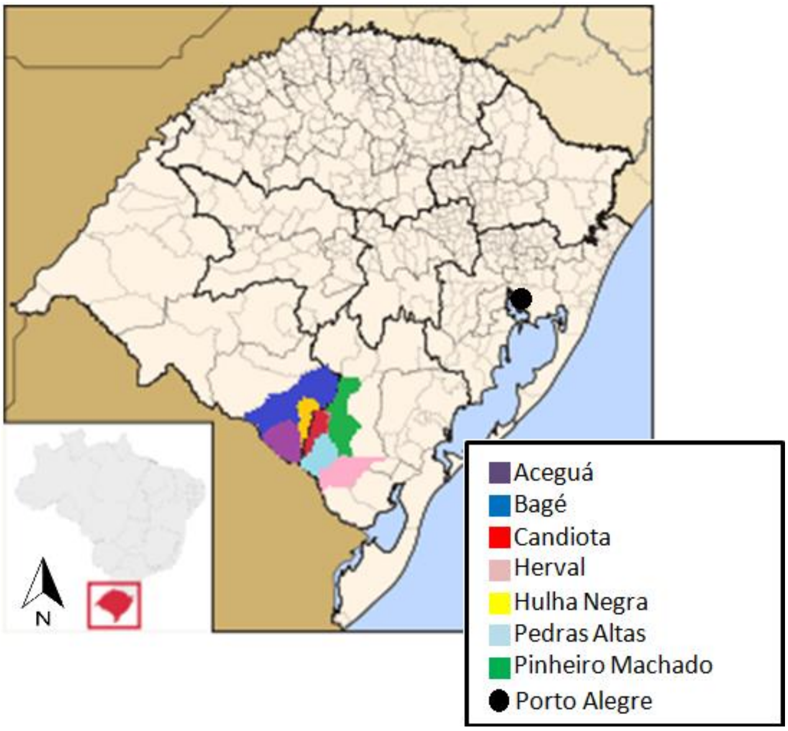

Figure 1. Map of the study region (Pinto et al 2017)

Environmental data

PM_{10} levels were estimated using a High Volume (HV) sampler installed at a monitoring station in the municipality of Candiota managed by the coal-fired power plant. The study considered the PM_{10} measurements of the Candiota station as the average for the entire study area and used the daily values between January 1, 2013 to December 31, 2013. The PM_{10} quantification was performed by b-ray attenuation mass monitor (BAM-1020 model), manufactured by Met One Instruments Inc.

As there is no monitoring of $PM_{2.5}$ levels from monitoring stations in the region, $PM_{2.5}$ values were estimated from the ratio obtained in a study in the region conducted by satellite data and which indicates that the ratio between $PM_{2.5}/PM_{10}$ is 0.67 (Da Silva Júnior et al. 2020).

Population and health data

The demographic and health data of the municipalities were collected through the database of the Unified Health System (DATASUS) in 2013 (DATASUS, 2020). Data on morbidity and mortality rates from cardiovascular and respiratory diseases, mortality from non-external causes and total population mortality were extracted.

Health Impact Assessment

The Health Impact Assessment was carried out according to the methodology of Pascal et al. (2013). Health benefits were evaluated by simulating two scenarios for each pollutant: decrease in average values by 5 µg/m^3 for $PM_{2.5}$ and for PM_{10} and scenarios in which the levels of the two pollutants would be within the limit imposed by WHO (WHO 2005) (WHO 2005): to 10 µg/m^3 for $PM_{2.5}$ and 20 µg/m^3 for PM_{10}.

For short-term exposure to PM_{10}, the health impact assessment was carried out using the equation below:

$$\Delta y = y_0\,(1 - e^{-\beta\Delta x}) \text{ (equation 1)}$$

Where:

Δy - decrease in health outcome associated with decrease in concentrations of pollutants, in annual number of deaths or hospitalizations.

y0 - baseline health outcome, in annual number of deaths or hospitalizations.

β - concentration response function coefficient.

Δx - decrease in the concentration of the pollutant in a given scenario, in µg/m^3

Regarding the exposure to long-term health effects of $PM_{2.5}$, we applied the standard summary life table methodology, as described by Pascal et al. (2013) calculated from the equation below:

$$nD_m{}^{impacted} = nD_x . e^{\beta^{\Delta} x} \text{ (equation 2)}$$

Where:

nDm - total number of deaths in the age group starting at age "n" for “m” years.

nDx is the number of deaths over a 5-year interval (starting at the age of 30 to the class of 85 or older)

The function was applied to groups of 5 years old from 30 years old, using the same β value for all age groups, in order to calculate the average potential gain in life expectancy. The results were expressed in number of deaths avoided and as gains in life expectancy in individuals over 30 years old. The annual survival burden, expressed as the total number of years of life that could have been gained, was calculated as the product of the average life expectancy at 30 years of age by the estimated number of the population at 30 years of age.

All Health Impact Assessment calculations were performed on the Microsoft Excel® spreadsheet developed by the Aphekom project, available at http://aphekom.org/web/aphekom.org/ All detailed equations are provided in these tools.

Deaths attributed to air pollution

The estimate of deaths related to air pollution was carried out according to Ostro (2004). The $PM_{2.5}$ data were used to measure cardiovascular mortality, using the annual mean of $PM_{2.5}$ (17.8 µg/m^3) and the background value of 7.5 µg/m^3 (Pope et al. 1995). To estimate deaths from non-external causes, the annual average of PM_{10} (26.7 µg / m3) was used and the background value used was 10 µg/m^3 (Ostro et al. 2004)

To estimate cardiovascular mortality and total mortality from non-external causes attributed to pollution, the following equations were used:

$$RR = [(X + 1)/(Xo + 1]^{\beta 1} \text{ (equation 3)}$$

$$RR = exp\ [\beta 2\ (X - Xo)] \text{ (equation 4)}$$

$$N_{assigned} = [(RR - 1)/RR]\ x\ N_{total} \text{ (equation 5)}$$

Where:

RR = Relative risk

X = average annual concentration of $PM_{2.5}$ (cardiovascular) or PM_{10} (total for non-external causes)

Xo = basal concentration of PM2.5 (cardiovascular) or PM10 (total for non-external causes)

β1 = concentration response function coefficient = 0.155515

β2 = concentration response function coefficient = 0.0008

$N_{assigned}$ = number of cardiovascular deaths or total from non-external causes

assigned to PM2.5 or PM10, respectively

N_{total} = total number of cardiovascular deaths or total from non-external causes

Economic evaluation on morbidity

The economic evaluation of expenses for hospitalizations due to respiratory and circulatory problems were calculated based on the average cost per day and the average hospital stay (Abe & Miraglia 2016). Data on hospitalization costs and average number of hospitalization days in the cities studied were obtained through the DATASUS database, referring to the year 2013.

The morbidity assessment was estimated according to Equation (6):

$$Ch = Vi\ x\ Nd\ x\ Nc \text{ (equation 6)}$$

Where:

Ch = Cost of hospitalization

Vi = unit value of a daily admission

Nd = average number of days of hospitalization due to a certain disease

Nc = number of cases due to a specific disease

Economic assessment of mortality> 30 years

The economic evaluation of mortality for> 30 years was estimated according to Corá et al. (2020) using Equation 7 below:

$$Cm = Vd \ x \ VSL \text{ (equation 7)}$$

Where:

Cm = health cost of mortality for people over 30 years old

Vd = deaths associated with air pollution

VSL = value of a statistical life, attributed to Bickel and Friedrich (2005) a value of € 1,000,000 and converted into reais. The following conversion was considered: 1 euro is equivalent to 6.80 Brazilian reais.

Results

The daily averages and the annual average of the PM_{10} and $PM_{2.5}$ are shown in Figure 2. The PM_{10} had an annual average of 26.7 μg/m^3 (min: 5 μg/m^3; max: 116 μg/m^3), while the $PM_{2.5}$ had an estimated annual average of 17.8 μg/m^3 (min: 3.35 μg/m^3; max: 77.2 μg/m^3).

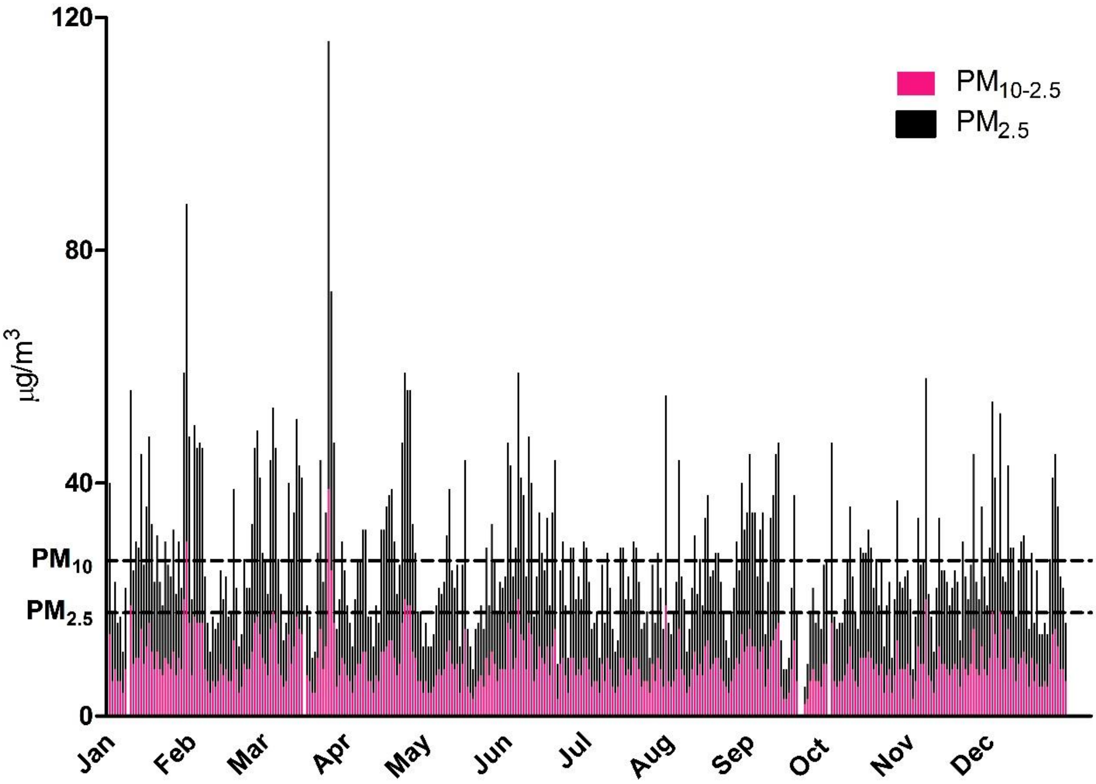

Figure 2. Daily averages of $PM_{10-2.5}$ (pink) and $PM_{2.5}$ (black) and the respective annual averages (---).

The estimate of deaths attributed to air pollution, as well as the annual number of hospitalizations (respiratory and cardiovascular) and total and non-external causes mortality in the study region (sum of the 7 cities in the year 2013), are shown in the Table 1. Among respiratory hospitalizations, we observed that individuals over the age of 65 represent 28.9% of cases. Of deaths from air pollution, mortality from non-external causes represented 10.3 cases, while cardiovascular mortality from 47.8 cases, equivalent to 0.8 and 11.6% of total deaths, respectively.

Table 1. Annual average of respiratory and cardiac hospitalizations and total mortality, due to non-external and cardiac causes in 2013 in the coal region, Brazil.

Health outcomes	ICD10 International Classification of Diseases and Health-Related Problems	Age	Annual average	Deaths attributed to air pollution	Percentage of deaths from air pollution	Annual average per 100,000 inhabitants
Total Mortality	A00-Y98	> 30	1,254	-	-	774,9
Cardiovascular Mortality	I00-I99	> 30	412	47,6	11,6	254,6
Mortality from non-external causes	A00-R99	All ages	1,232	10,3	0,8	761,4
Cardiac Hospitalizations	I00-I52	All ages	1,922	-	-	1187,8
Respiratory hospitalizations	J00-J99	All ages	1,944	-	-	1201,4
Respiratory hospitalizations	J00-J99	15-64	444	-	-	274,4
Respiratory hospitalizations	J00-J99	> 65	561			346,7

Table 2 shows the potential benefits in reducing $PM_{2.5}$ in the study region, simulating two possible scenarios: reduction of 5 µg/m^3 in the annual average to PM_{10} and $PM_{2.5}$ and reduction until legal limits (10 µg/m^3 to $PM_{2.5}$ and 20 µg/m^3 to PM_{10}). With a reduction of 5 µg/m^3 of $PM_{2.5}$, there would be 12 annual deaths avoided and 7 annual cardiovascular deaths avoided. Still, a gain of 10.8 months of life expectancy. Already simulating the scenario with a decrease to 10 µg/m^3 of $PM_{2.5}$ (OMS and Brazilian limit), 18 deaths due to total mortality and 11 cardiovascular would be avoided. The gain in life expectancy would be almost a year and a half (17.5 months). In these scenarios, the reduction in expenses with total mortality would be 26,674,656,2 dollars (reduction of 5 µg/m^3) and 41,509,031,4 dollars (reduction to 10 µg/m^3).

Table 2. Potential health benefits of reducing daily $PM_{2.5}$ levels in hospitalizations and mortality from non-external causes and cardiovascular mortality, in the coal region, Brazil (2013).

	Annual number of deaths avoided	**Annual number of deaths averted per 100,000 population**	**Life expectancy gain (months)**	**Life years gain**	**Monetary gains US$**
			Decrease of 5 $\mu g/m^3$ of $PM_{2.5}$		
Total mortality	12,0	13,4	10,8	2136,3	26,674,656,2
Cardiovascular mortality	7,6	8,5	-	-	-
			Decrease to 10 $\mu g/m^3$ of $PM_{2.5}$		
Total mortality	18,7	21,1	17,2	3400,6	41,509,031,4
Cardiovascular mortality	11,8	13,2	-	-	-

The potential health benefits of reducing PM_{10} levels by 5 $\mu g/m^3$ would be 16 hospitalizations (11 respiratory and 5 cardiovascular) and 3.7 deaths from avoided non-external causes. In relation to economic benefits, the reduction in spending on respiratory hospitalizations would be $ 2,272,446, cardiac hospitalizations $ 2,121,746 and with mortality $ 5,035,521,854. In a scenario of a decrease to 20 $\mu g/m^3$ of PM_{10}, the potential health benefits would be 21 hospitalizations (14 respiratory and 7 cardiac), and 5 deaths from prevented non-external causes. These health benefits would represent savings of $ 5,903,032 dollars in hospitalizations (respiratory and cardiac) and $ 6,668,664,076 million dollars in mortality from non-external causes (Table 3).

Table 3. Potential health benefits of reducing daily PM_{10} levels in hospitalizations and mortality from non-external causes and cardiovascular mortality, in the coal region, Brazil (2013).

	Annual number of deaths avoided	**Annual number of deaths avoided per 100,000 inhabitants**	**Monetary gains US$**
	Decrease of 5 μg/m³ of PM_{10}		
Total mortality from non-external causes	3,7	2,27	5,035,521,854
Respiratory hospitalizations	11,0	6,79	2,272,446
Cardiac hospitalizations	5,7	3,55	2,121,746
	Decrease to 20 μg/m³ of PM_{10}		
Total mortality from non-external causes	4,9	3,05	6,668,664,076
Respiratory hospitalizations	14,7	9,11	3,036,814
Cardiac hospitalizations	7,7	4,76	2,866,218

Discussion

The findings of the present study estimated that a percentage greater than 11% of deaths from cardiovascular diseases among those over 30 years of age are attributable to pollution by $PM_{2.5}$ and almost 1% of total deaths from non-external causes for all ages associated with the levels of PM_{10} in the region. The study also showed the health benefits associated with the reduction of PM levels, in terms of reducing deaths, hospitalizations and economic costs, in addition to increasing life expectancy in the study region. This scenario of potential benefits is extremely relevant in the study region, since according to data from the Ministry of Health (DATASUS 2021), the highest mortality rates are related to cardiovascular diseases, tumors and diseases of the respiratory tract, which are closely related. relation to air pollution.

A study based on data from 185 countries estimated that exposure to $PM_{2.5}$ is responsible for the reduction of the global life expectancy in approximately 1 year and that the reduction of 10 µg/m^3 in the levels of this pollutant would be responsible for the increase of 0.6 years of life in global life expectancy, having an impact equivalent to the eradication of cases of lung and breast cancers (Apte et al. 2018). In the context of Latin American countries, the impacts of air pollution on health services are still poorly understood. In the case of Brazil, less than 2% of cities have air quality monitoring stations (Réquia et al. 2015), restricting studies that estimate the impacts on the population's health to large national metropolises (Abe & Miraglia 2016, Leão et al. 2021).

In addition to the large metropolises, Brazil has regions with high levels of air pollution related to other sources, such as fires (Marlier et al. 2020) and activities for the extraction and use of ores (Da Silva Júnior et al. 2020). The country has one of the largest reserves of mineral coal in the world and the region of the present study concentrates 40% of all national reserves (ANEEL 2008). In other regions of the world, some studies in coal mining areas have already shown the impact of air pollution on health indicators and the benefits associated with reducing pollutant levels, especially PM (Mokhtar et al. 2014, Chio et al 2019).

The potential health benefits associated with the reduction in the levels of pollution of PM_{10} and $PM_{2.5}$ in the present study is fundamental to show the government and society that the adoption of stricter air pollution control policies can have social and economic impacts improving the quality of life and the economy at the local level. Brazil belatedly adopted the levels stipulated by the WHO (WHO 2006) through CONAMA Resolution 491 (CONAMA 2018). The previous legislation (CONAMA 1990), besides admitting daily limits of PM_{10} three times higher than the WHO limits, did not contemplate $PM_{2.5}$.

The data in the present study refer to values prior to the implementation of the new national legislation that imposes stricter limits on air pollutants and future studies should investigate the impact of the new legislation on the levels of the pollutants and on the potential health benefits. Government actions in proposing stricter environmental laws combined with the commitment of different industrial sectors can be effective in reducing air pollution and its consequent health benefits. In the sense, a study conducted in the North American state of North Carolina (NC), from the establishment of an environmental law stricter than the rules imposed by the federal government in 2002, followed the levels of sulfur dioxide (SO_2) and associated sulfate to $PM_{2.5}$ between 2002-2012 and revealed significant reductions in the levels of these two pollutants (-20.3% / year for SO_2 and -8.7% / year for sulfate associated with $PM_{2.5}$), especially in the region that concentrates 9 of the 14 largest coal-fired power plants in the NC. This reduction in air pollution resulted in 1700 deaths avoided in 2012 (Li & Gibson 2014).

Discussions about the damage of air pollution to health need to go beyond the limits of the environmental sphere and become a recurring theme in the daily lives of doctors and other health professionals (Iriti et al. 2020), since exposure to air pollutants kills more people worldwide each year than diseases such as HIV / AIDS, malaria and tuberculosis (Landrigan 2017) and is responsible for 19% of all deaths from cardiovascular disease, 24% of deaths from heart ischemia, 21% of deaths from stroke and 23% of lung cancer deaths (Wang et al. 2015). These concerns should be further reinforced in areas of socioeconomic vulnerability and inequality, since the severity of the health effects resulting from air pollution seems to have relationship with economic indicators (Lipfert 2004) and development (Mannucci & Franchini 2017).

Numerous studies carried out in the region show negative outcomes in this population (Pinto et al 2017, Dos Santos et al 2018, Dos Santos et al 2021a, Bigliardi et al 2021, Dupont-

Soares et al 2021), which is exposed to environmental pollutants and is socioeconomically vulnerable. Other studies have been concerned with estimating the environmental risk of exposure to pollutants present in different compartments in the region (Bonifácio et al 2021, Dos Santos et al 2021b, Müller et al 2021), revealing a scenario of exposure to pollutants across different pollutants and environmental compartments.

The current study scales the deaths attributed to air pollution, as well as the potential benefits of reducing PM_{10} and $PM_{2.5}$ levels. These unprecedented findings may serve as subsidies for health surveillance and for new epidemiological studies, since there is a forecast for the creation of new coal-fired power plants in the region. The health and economic benefits need to be taken into account when planning future actions in the region. A study carried out in Northeast Brazil estimated that the restriction of PM_{10} emission standards generates economic gains related to health benefits that exceed by more than 60 times the costs of controlling air pollutant emissions in new coal-fired power plants (Howard et al 2019).

Conclusion

In Brazil, mainly in the extreme South, where there are large reserves of coal, coal-fired power plants are likely to continue to play an important role, as they are the basis of the economy for countless poor municipalities. However, the current study showed that air pollution has an important contribution to preventable deaths. Approximately 11% of deaths from cardiovascular problems are attributable to the levels of $PM_{2.5}$ and the reduction in the levels of PM_{10} and $PM_{2.5}$ can bring benefits in health indicators and associated cost reductions. These new findings are important instruments available to decision makers, with a view to improving environmental legislation and in the planning of new enterprises.

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5.2. ARTIGO 2

Human Health Risk Assessment of Air Pollutants in the Largest Coal Mining Area in Brazil

Submetido na

Environmental Science and Pollution Research

HUMAN HEALTH RISK ASSESSMENT OF AIR POLLUTANTS IN THE LARGEST COAL MINING AREA IN BRAZIL

Laiz Coutelle Honscha[1], Fernanda Oliveira Reis[1], Priscila Aikawa[1], Mariana Vieira Coronas[2], Ana Luíza Muccillo-Baisch[1], Paulo Roberto Martins Baisch[1], Flavio Manoel Rodrigues da Silva Júnior[1]*

[1] Universidade Federal do Rio Grande – FURG, Avenida Itália, km 8, S/N, Campus Carreiros, Rio Grande, RS, Brazil 96203900
[2] Universidade Federal de Santa Maria, Campus de Cachoeira do Sul, Rodovia Taufik Germano, 3013, Passo D'Areia Cachoeira do Sul, Rio Grande do Sul – Brazil 96503-205

*corresponding author – f.m.r.silvajunior@gmail.com + 55 53 32336500

Abstract

The Candiota region, located in the extreme south of Brazil, has the largest mineral coal deposit in the country, and this activity is capable of releasing pollutants in which they are associated with the contamination of different matrices (soil, water and air). The present study aimed to carry out a risk assessment to human health of atmospheric pollutants NO_2 and SO_2 and PM_{10}-bound metal(loid)s in the municipality of Candiota, in addition to evaluating the correlation of meteorological parameters for the dynamics and potential risk of these pollutants. Pollutants were sampled from stations located almost 4 km from coal exploration activities and the trace elements As, Cd, Se, Pb and Ni, in addition to NO_2 and SO_2, were evaluated. Risk assessment was conducted taking into account the risk to adults via the inhalation route. During the sampling period, all pollutants presented values lower than national legislation or internationally accepted values and Pb was the element that presented the highest values throughout the sampled period. The risk assessment showed no carcinogenic and non-carcinogenic risk, even when considering the sum of the risk of all analyzed pollutants. It can be observed that the highest levels of Pb, As and Se occurred in the winter season, while the levels of Ni and Cd were higher in the spring and the meteorological parameters were correlated with the pollutants, even using a temporal lag of 5 days. Although the air pollutants evaluated did not present a risk to human health, continuous monitoring of regions with strong mineral exploration activity must be carried out with a view to maintaining the well-being of exposed populations, mainly because there are people living in areas closer to sources of coal pollution than distance to air quality monitoring stations.

Keywords: Air pollution, metals, metalloids, Candiota, USEPA.

INTRODUCTION

Air pollution is largely related to adverse effects on human health, becoming a worldwide problem. Among the main effects observed, irritation in the throat, eyes and nose, allergic and cardiovascular diseases, respiratory problems and lung cancer stand out (Zhang *et al*., 2018; Khafaie *et al*., 2016; Schraufnagel *et al*., 2018; Xing *et al*., 2019). These damages are associated with the presence of chemical substances which are released into the atmosphere through natural sources, but mainly anthropogenic actions (Ogino *et al*., 2019).

The World Health Organization (WHO) has global air quality guidelines, which include particulate matter (PM_{10} and $PM_{2.5}$), ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxide (SO_2) and carbon monoxide (CO) (WHO, 2021). Particulate matter (PM) is classified according to its diameter and the particles of greatest interest to human health are coarse inhalable particles (PM_{10}) and fine inhalable particles ($PM_{2.5}$) (CONAMA, 2018).

Among the components of PM are metals, such as lead, iron, copper and chromium, which are released into the atmosphere mainly by industrial activities (Xue *et al*., 2018). Studies have shown that prolonged exposure to these chemical elements, at high levels, is related to several adverse effects on human health, including hematological, gastrointestinal, neurological dysfunction, and reproductive impairment (Charkiewicz & Backstrand, 2020), and micronucleus induction and oxidative damage (Bocchi *et al*., 2019). Carcinogenic risks through human exposure to PM_{10}-bound metals and metalloids may present a low risk when evaluating the metals individually, but when represented by the sum of all metals and metalloids, the risk may exceed the safety level (Guo *et al*., 2018).

In addition to PM constituents, gaseous pollutants have been associated with severe health damage. Sulfur dioxide is a gas released into the atmosphere primarily through the burning of sulfur-containing fuels, such as diesel oil, industrial fuel oil, and gasoline (CETESB, 2022). Inhalation of this pollutant is associated with eye irritation, respiratory disease, pulmonary edema, heart disease and premature death (Khaniabadi *et al*., 2018; Khaniabadi *et al.*, 2017). Nitrogen dioxide, in turn, is released mainly by vehicle exhausts. Human exposure to this pollutant can generate irritation in the airways, as well as short-term exposure can aggravate respiratory diseases, such as asthma, and coughing, wheezing, breathing difficulties, among others (EPA, 2022).

Mining activities are known to release chemical substances such as metals into the environment and studies have shown that increasing concentrations of metals near mining areas can have negative effects on human health (Xie *et al*., 2017, Zhang *et al*., 2020; Briki *et al*., 2017). The municipality of Candiota, located in the south of Brazil, has the largest mineral coal deposit in the country, with an area of approximately 2,000 km^2 which has been mined in the open since 1961. The mineral coal from Candiota has levels of elements higher or very close to the maximum contents of coal samples from other locations, among these elements we have As, Cd, Pb, Zn, Ca, Fe, Mg, Mg and Ni (Pires *et al*., 2001).

Given the potential contamination of different environmental compartments, numerous studies have been carried out in this area to assess the impact on the health of adult and child residents (Da Silva Pinto *et al*., 2017; dos Santos *et al*., 2018; Bigliardi *et al*., 2020; dos Santos *et al*., 2020a; dos Santos *et al*., 2020b, dos Santos *et al*., 2019a), workers (Da Silva Júnior *et al*., 2017; dos Santos *et al*., 2019b) and environmental matrices (Da Silva Júnior *et al*., 2019). A recent study by Honscha *et al* (2021) estimated the total mortality, cardiovascular disease, and hospitalizations for heart and respiratory problems attributed to particulate matter (PM_{10} and $PM_{2.5}$) as well as the benefits related to reduced air pollution, and concluded that more than 11% of cardiovascular deaths were attributed to $PM_{2.5}$ pollution. Furthermore, the authors showed that a scenario of $PM_{2.5}$ reduction of 5ug/m^3 would be able to increase life expectancy by 10.8 months, while a reduction of 10ug/m^3 would be able to increase life expectancy by 17.5 months in the population of the study region.

Human health risk assessment has been a strategy used in the study region to estimate the risk of exposure of the local population to contaminants present in water (da Silva Bonifácio *et al*., 2021), in the soil (Penteado *et al*., 2021; Ramires *et al*., 2022), air (Müller *et al*., 2021) and food (dos Santos *et al*., 2020). Thus, the risk assessment methodology has been identified as useful for estimating the non-carcinogenic and carcinogenic risks to human health exposed to chemical substances. (de Brum *et al*., 2021; EPA, 2009) being used in risk studies of populations exposed to contaminants from mining areas through different exposure routes (Roy *et al*., 2019; Focus *et al*., 2021; Adewumi & Laniyan, 2020).

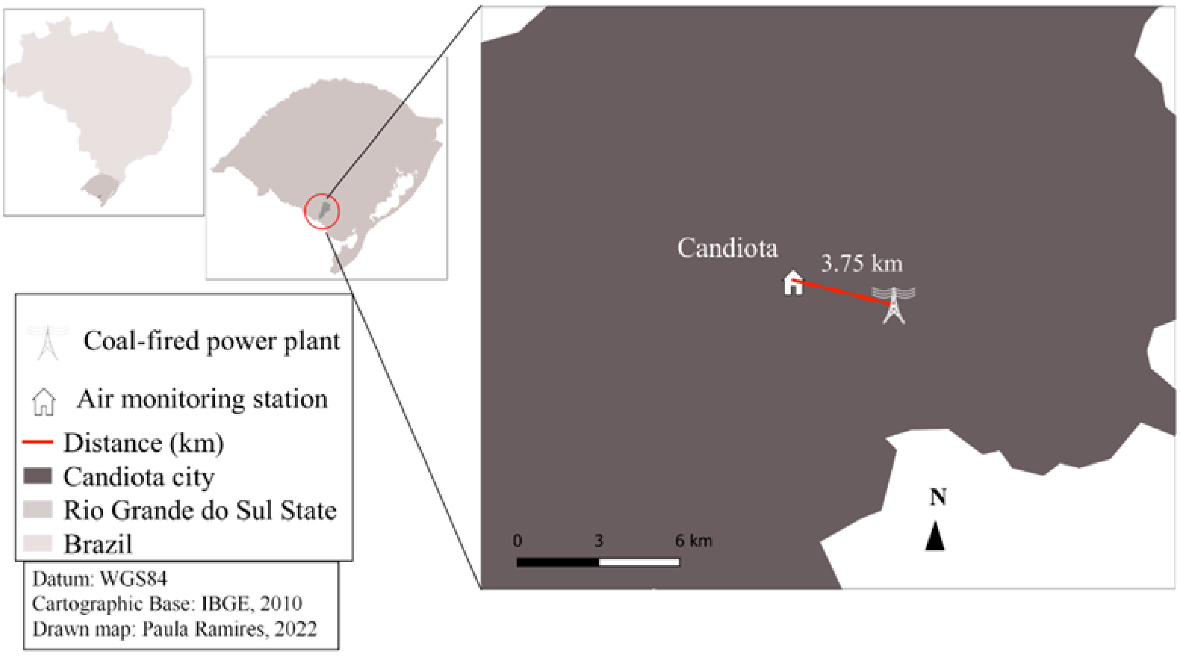
Human health risk assessment studies in mining areas have been studying chemical substances and their possible non-carcinogenic and carcinogenic health effects in isolation. NO_2 and SO_2 and PM_{10}-bound metal(loid)s in Candiota city, evaluating the contribution of meteorological parameters to the dynamics and potential risk of these pollutants.

MATERIAL AND METHODS

Study region

The study was carried out in the municipality of Candiota located in the state of Rio Grande do Sul, in the extreme south of Brazil. Candiota is located 50 km from the Uruguayan border and 410 km from the state capital, Porto Alegre. PM_{10}, NO_2 and SO_2 measurements were carried out at an air sampling automatic station (Candiota Station), which is the closest station to the main sources of coal exploration (mining and thermoelectric plant), located in the Dario Lassence neighborhood, having 3.75 km away from the emitting source (Figure 1).

The analysis of PM_{10}-bound metal(loid)s was carried out from the exposure and collection of filters in a large volume air sampler (Hi-Vol) located in the same area as the automatic monitoring station. The geographic coordinates of the location of the monitoring point (air quality monitoring network) are Latitude: 31°32'35.77"S Longitude: 53°42'55.87"W.



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Metal(loid)s present in PM_{10}

Trace elements (metals and metalloids) evaluated in PM10 (As, Cd, Se, Pb and Ni) were analyzed using quartz filters for PM10 sampling using a large volume air sampler for 24 hours. The analysis of metal(loid)s was performed according to the methodology of USEPA (1999) using acid with aqua regia (HNO3 and HCl 3:1) for microwave digestion. Afterwards, the extract was filtered and diluted in milliQ water. The determinations were carried out by graphite furnace Atomic Absorption spectrophotometry in a Perkin Elmer Analyst 800 model.

Nitrogen Dioxide (NO_2) and Sulfur Dioxide (SO_2)

Nitrogen dioxide (NO_2) was measured using the chemiluminescence method, using a HORIBA analyzer model APNA-360 and APNA-37CE, thus meeting the requirements of the USEPA Reference Method RFNA-0506-1517. Sulfur dioxide (SO_2) was measured using the Ultraviolet Fluorescence method using HORIBA brand analyzers model APSA-360 and APSA-37CE, thus meeting the requirements of USEPA Reference Method EQSA-0506-159.

Meteorological data

Meteorological data were obtained through the National Institute of Meteorology (INMET), from the monitoring station closest to the study site, located in the municipality of Bagé. In order to correlate meteorological data with atmospheric pollutants (metals and gases) as well as with non-carcinogenic and carcinogenic risks to human health, the data obtained were: daily average of instantaneous temperature (C), humidity (%), pressure (hPa), wind speed (m/s), wind direction (m/s) and daily rainfall (mm).

Correlation analysis

A Pearson correlation analysis was conducted between air pollutants and a second correlation analysis between air pollutants and meteorological variables, considering a temporal lag of 5 days for the meteorological data. The value of $p<0.05$ was used as critical for correlation significance.

Human health risk assessment (HHRA)

The human health risk assessment was carried out for adults, being evaluated through the inhalation route of exposure (EPA, 2009). To characterize the risk of metal(loid)s, classified as carcinogenic (As and Cd), possibly carcinogenic (Pb and Ni) and non-carcinogenic (Se), the reference concentration (Rfc) and the unit inhalation risk (IUR) (Table 1) of each element. The mathematical models used to assess the risk of trace elements and NO_2 and SO_2 were performed according to EPA (1989):

$$EC\ (\mu g/m^3) = \frac{CA \times EF \times ET \times ED}{AT}$$

where EC is the exposure concentration (ug/m^3), CA: concentration of the contaminant in the air (ug/m^3), EF: exposure frequency (days/year), ET: exposure time (24h/day), ED: exposure duration (years), AT: mean non-carcinogenic time is the exposure duration (years) × 365 days (days/year) × 24h/day and AT: carcinogenic is 70 years × 365 days (days/year) (Table 2).

To calculate the inhalation risk quotient, the formula described below was used:

$$HQ = \frac{EC\ (\mu g/m^3)}{RfC\ (mg/m^3) \times 1000\mu g/mg}$$

Where HQ is the non-cancer risk of exposure to a particular element, Rfc: is the reference inhalation concentration (mg/m³-day). If HQ < 1: the risk of non-carcinogenic effects is believed not to be prominent, if HQ > 1: indicates a considerably high non-carcinogenic effect.

The inhalation risk (Risk) of air was calculated using the following formula:

$$Risk = \mathrm{IUR}(\mu g/m^3) \times EC(\mu g/m^3)$$

where IUR is the unit inhalation risk. The acceptable or tolerable risk is 1×10^{-6} to 1×10^{-4}.

Table 1. RfC and IUR values of analyzed pollutants

	RfC	**IUR**
As	1,50E-05	4,30E-03
Cd	1,00E-05	1,80E-03
Se	2,00E-02	-
Pb	-	1,00E+00
Ni	1,40E-05	4,80E-04
NO_2	2,00E+01	-
SO_2	3,00E+01	-

Table 2. Input parameters and abbreviations for cancer and non-cancer exposure assessment.

Parameter	**Abbreviation**	**Unit**	**Value**	**References**
Metal concentration in PM_{10} or gases	CA	ug/m³	Table 2	This study
Average lifetime	AT	hours	ED×365×24 (for non-carcinogens) 70×365×24 (for carcinogens)	EPA (2001)
Exposure duration	ED	year	24	EPA (2001)
Exposure frequency	EF	days/year	350	Wang (2018)
Exposure time	ET	h/day	24	EPA (2001)

RESULTS

Concentrations of metal(loid)s in PM_{10}

The concentrations of metal(loid)s in PM_{10} are shown in Table 3. The trace element that showed the highest concentration values throughout the sampled year was Pb, where its highest concentration was 0.16 ug/m³ and the lowest was 0. 0039 ug/m³, followed by Ni, As, Se and Cd respectively, with the lowest concentration of Pb being above the highest concentration found in all other elements.

Table 3. Metal(loid) concentrations in PM_{10} during the collection period

		Concentration in PM_{10}				
Season	**Date**	**As (ng/m³)**	**Cd (ng/m³)**	**Se (ng/m³)**	**Pb (ng/m³)**	**Ni (ng/m³)**
Winter	**Aug, 21**	0.573	0.062	0.209	19.242	2.193
Winter	**Aug, 27**	0.488	0.046	1.082	11.327	1.434
Winter	**Sept, 02**	1.237	0.124	0.306	27.204	1.435
Winter	**Sept, 08**	0.05	0.048	0.229	20.028	0.906
Winter	**Sept, 14**	0.238	0.16	0.155	160.31	0.759
Winter	**Sept, 20**	1.509	0.036	0.623	22.967	0.789
Spring	**Sept, 26**	0.42	0.069	0.182	7.449	0.823
Spring	**Oct, 02**	0.089	0.026	0.255	7.566	0.911
Spring	**Oct, 08**	0.322	0.056	0.146	3.924	0.498
Spring	**Oct, 14**	0.112	0.116	0.192	13.093	0.856
Spring	**Oct, 20**	0.163	0.1	0.208	14.345	0.537
Spring	**Oct, 26**	0.387	0.33	0.671	44.482	2.325
Spring	**Nov, 01**	0.138	0.089	0.18	14.062	0.546
Spring	**Nov, 07**	0.063	0.073	0.175	6.187	0.72
Spring	**Nov, 13**	0.05	0.058	0.213	5.993	0.621
Spring	**Nov, 19**	0.287	0.05	0.116	7.827	0.666
Spring	**Nov, 25**	0.371	0.058	0.528	10.267	0.879
Spring	**Dec, 01**	0.153	0.143	0.1	147.031	0.584
Spring	**Dec, 07**	0.026	0.084	0.156	8.25	0.575
Spring	**Dec, 13**	0.245	0.079	0.164	14.542	0.694
Spring	**Dec, 20**	0.426	0.126	0.407	7.47	0.653
Summer	**Dec, 26**	0.413	0.085	0.13	12.192	0.686

The highest concentrations of metal(loid)s during the study period were variable. Pb had the highest concentrations in mid-September and early December (Figure 2.a), while Ni and Cd had their highest concentrations in late October, As in late September and late August (Figure 2.b).

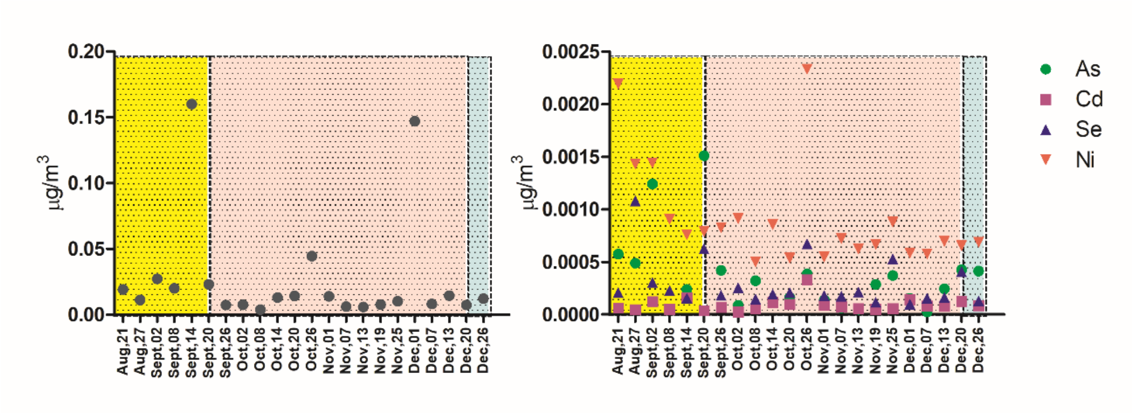

Figure 2. Concentrations of metals present in PM_{10} according to the sampled period. (a) Pb; (b) As, Cd, Se and Ni. The period in yellow refers to winter, the period in pink refers to spring and the period in blue refers to summer.

NO_2 and SO_2 concentration

The concentrations of NO_2 and SO_2 are shown in Figure 3. It can be seen that the highest concentration found for sulfur dioxide (SO_2) was 19.13 µg/m³, being very close to the maximum value allowed by Brazilian legislation (20 µg/m³) in a 24-hour period. The same occurred for nitrogen dioxide (NO_2), where the highest value found was 8.71 µg/m³, not exceeding the maximum value legally stipulated in Brazil (200 µg/m³), a value referring to the hourly average.

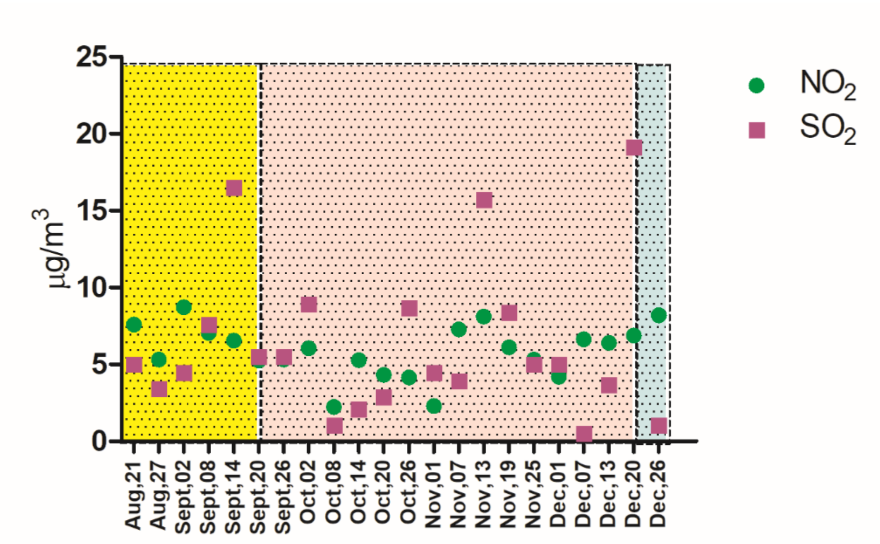

Figure 3. Concentration of NO_2 and SO_2 according to the sampled period. The period in yellow refers to winter, the period in pink refers to spring and the period in blue refers to summer.

Correlation between air pollutants

Based on the results obtained, it can be observed that there was a moderate positive correlation between the metals Cd and Pb, Cd and Ni, Se and Ni as well as between PM_{10} and NO_2 (Table 4).

Table 4. Correlation between metal(loid)s, PM_{10} and gases (NO_2 and SO_2).

	As	**Cd**	**Se**	**Pb**	**Ni**	**PM_{10}**	**NO_2**	**SO_2**	**Legend**	**r**
As	1,0000	-0,0212	0,4186	-0,0409	0,3195	0,1840	0,1476	-0,0647		> 0,81
Cd		1,0000	0,1312	**0,4473***	**0,4602***	-0,3036	-0,1612	0,2158		> 0,61
Se			1,0000	-0,1394	**0,4812***	-0,2352	-0,1155	0,0468		> 0,41
Pb				1,0000	0,0042	-0,3949	-0,0858	0,2943		> 0,21
Ni					1,0000	-0,1016	0,1570	0,0033		< -0,8
PM10						1,0000	**0,5257***	-0,2132		< -0,61
NO2							1,0000	0,2722		< -0,41
SO2								1,0000		< -0,21

*$P < 0.05$

Meteorological data

The meteorological parameters, temperature, humidity, pressure, wind speed, wind direction and rainfall according to the sampling dates are available in the supplementary material (Table S1) and refer to information for the winter, spring and early summer.

Correlation analyzes between air pollutants and meteorological data were carried out on the day of sampling of PM_{10} and NO_2 and SO_2 gases, and data from a temporal lag of 1 to 5 days before the sampling period were also evaluated (Tables S2 the S7).

The correlation between pollutants and meteorological parameters for the same sampling day showed a strong positive correlation between Cd metal and rainfall. The chemical element Ni showed moderate positive correlation with the humidity and rainfall. PM_{10}, on the other hand, showed a moderate negative correlation for humidity and rainfall, while Se and NO_2 showed moderate correlation with the temperature and wind speed, respectively (Table S2).

The correlation found for the day before the collections showed a moderate correlation for Se with atmospheric pressure. PM_{10} and NO_2, on the other hand, showed a moderate negative correlation for pressure, As for humidity and Se for temperature (Table S3). Regarding the correlation performed for two days before the collections, a moderate positive correlation can be observed for Se and wind speed, as well as a moderate negative correction for Se and temperature, Pb and humidity and SO2 and pressure (Table S4).

Correlations for three days before collections show a moderate negative correlation for Se and temperature (Table S5). The correlation of four days before the collections shows a moderate positive correlation for the chemical element Ni and the pressure, also presenting a moderate negative correlation for the Ni and the temperature (Table S6).

Finally, the correlation for five days before the collections shows a strong positive correlation for As and Se for rain, moderate positive correlation for Se and humidity, as well as a moderate negative correlation for Ni and temperature (Table S7).

Human health risk assessment

The results obtained for the non-carcinogenic and carcinogenic risks of metal(loid)s in PM_{10} and NO_2 and SO_2 are presented in Tables 4 and 5. It can be observed that for the non-carcinogenic risk of metal(loid)s and NO_2 and SO_2 when evaluated separately and after the sum of the metal(loid)s and NO_2 and SO_2, the values did not exceed the safety level (HQ = 1), thus indicating that these pollutants at the concentrations sampled did not result in non-carcinogenic effects for adults (Table 4). Similarly, there were no carcinogenic effects of the metal(loid)s and the risk values are within the acceptable limit for human health (risk > 1×10^{-6}) when evaluated separately and after the sum (Table 5).

Table 4. Non-carcinogenic risk for metal(loid)s, NO_2 and SO_2.

ADULTS								
Non-carcinogenic								
DATE	**As**	**Cd**	**Se**	**Pb**	**Ni**	**NO_2**	**SO_2**	**Σ***
Aug, 21	3.66E-02	5.95E-03	1.00E-05	9.23E-02	1.50E-01	3.64E-04	1.59E-04	**2.86E-01**
Aug, 27	3.12E-02	4.41E-03	5.19E-05	5.43E-02	9.82E-02	2.55E-04	1.09E-04	**1.89E-01**
Sept, 02	7.91E-02	1.19E-02	1.47E-05	1.30E-01	9.83E-02	4.18E-04	1.42E-04	**3.20E-01**
Sept, 08	3.20E-03	4.60E-03	1.10E-05	9.60E-02	6.21E-02	3.39E-04	2.43E-04	**1.66E-01**
Sept, 14	1.52E-02	1.53E-02	7.43E-06	7.69E-01	5.20E-02	3.14E-04	5.28E-04	**8.52E-01**
Sept, 20	9.65E-02	3.45E-03	2.99E-05	1.10E-01	5.40E-02	2.52E-04	1.76E-04	**2.65E-01**
Sept, 26	2.68E-02	6.62E-03	8.73E-06	3.57E-02	5.64E-02	2.56E-04	1.76E-04	**1.26E-01**
Oct, 02	5.69E-03	2.49E-03	1.22E-05	3.63E-02	6.24E-02	2.90E-04	2.85E-04	**1.07E-01**
Oct, 08	2.06E-02	5.37E-03	7.00E-06	1.88E-02	3.41E-02	1.07E-04	3.35E-05	**7.90E-02**
Oct, 14	7.16E-03	1.11E-02	9.21E-06	6.28E-02	5.86E-02	2.53E-04	6.70E-05	**1.40E-01**
Oct, 20	1.04E-02	9.59E-03	9.97E-06	6.88E-02	3.68E-02	2.08E-04	9.21E-05	**1.26E-01**
Oct, 26	2.47E-02	3.16E-02	3.22E-05	2.13E-01	1.59E-01	2.00E-04	2.76E-04	**4.29E-01**
Nov, 01	8.82E-03	8.53E-03	8.63E-06	6.74E-02	3.74E-02	1.10E-04	1.42E-04	**1.22E-01**
Nov, 07	4.03E-03	7.00E-03	8.39E-06	2.97E-02	4.93E-02	3.49E-04	1.26E-04	**9.05E-02**
Nov, 13	3.20E-03	5.56E-03	1.02E-05	2.87E-02	4.25E-02	3.89E-04	5.02E-04	**8.09E-02**
Nov, 19	1.83E-02	4.79E-03	5.56E-06	3.75E-02	4.56E-02	2.93E-04	2.68E-04	**1.07E-01**
Nov, 25	2.37E-02	5.56E-03	2.53E-05	4.92E-02	6.02E-02	2.56E-04	1.59E-04	**1.39E-01**
Dec, 01	9.78E-03	1.37E-02	4.79E-06	7.05E-01	4.00E-02	2.01E-04	1.59E-04	**7.69E-01**
Dec, 07	1.66E-03	7.77E-03	7.48E-06	3.96E-02	3.94E-02	3.18E-04	1.67E-05	**8.87E-02**
Dec, 13	1.57E-02	7.58E-03	7.86E-06	6.97E-02	4.75E-02	3.08E-04	1.17E-04	**1.41E-01**
Dec, 20	2.72E-02	1.21E-02	1.95E-05	3.58E-02	4.47E-02	3.30E-04	6.11E-04	**1.21E-01**
Dec, 26	2.64E-02	8.15E-03	6.23E-06	5.85E-02	4.70E-02	3.93E-04	3.35E-05	**1.40E-01**

** Σ= Sum Carcinogenic Risk for Metal(loid)s, NO_2 and SO_2*

Table 5. Carcinogenic risk for metal(loid)s.

ADULTS					
Carcinogenic Risk					
DATE	As	Cd	Pb	Ni	Σ*
Aug, 21	8.10E-07	3.67E-08	6.96E-08	3.46E-07	**1.26E-06**
Aug, 27	6.90E-07	2.72E-08	4.10E-08	2.26E-07	**9.84E-07**
Sept, 02	1.75E-06	7.34E-08	9.84E-08	2.26E-07	**2.15E-06**
Sept, 08	7.07E-08	2.84E-08	7.24E-08	1.43E-07	**3.14E-07**
Sept, 14	3.36E-07	9.47E-08	5.80E-07	1.20E-07	**1.13E-06**
Sept, 20	2.13E-06	2.13E-08	8.31E-08	1.25E-07	**2.36E-06**
Sept, 26	5.94E-07	4.08E-08	2.69E-08	1.30E-07	**7.91E-07**
Oct, 02	1.26E-07	1.54E-08	2.74E-08	1.44E-07	**3.12E-07**
Oct, 08	4.55E-07	3.31E-08	1.42E-08	7.86E-08	**5.81E-07**
Oct, 14	1.58E-07	6.86E-08	4.74E-08	1.35E-07	**4.09E-07**
Oct, 20	2.30E-07	5.92E-08	5.19E-08	8.47E-08	**4.26E-07**
Oct, 26	5.47E-07	1.95E-07	1.61E-07	3.67E-07	**1.27E-06**
Nov, 01	1.95E-07	5.27E-08	5.09E-08	8.62E-08	**3.85E-07**
Nov, 07	8.91E-08	4.32E-08	2.24E-08	1.14E-07	**2.68E-07**
Nov, 13	7.07E-08	3.43E-08	2.17E-08	9.80E-08	**2.25E-07**
Nov, 19	4.06E-07	2.96E-08	2.83E-08	1.05E-07	**5.69E-07**
Nov, 25	5.24E-07	3.43E-08	3.71E-08	1.39E-07	**7.35E-07**
Dec, 01	2.16E-07	8.46E-08	5.32E-07	9.22E-08	**9.25E-07**
Dec, 07	3.68E-08	4.79E-08	2.98E-08	9.07E-08	**2.05E-07**
Dec, 13	3.46E-07	4.68E-08	5.26E-08	1.10E-07	**5.55E-07**
Dec, 20	6.02E-07	7.46E-08	2.70E-08	1.03E-07	**8.07E-07**
Dec, 26	5.84E-07	5.03E-08	4.41E-08	1.08E-07	**7.87E-07**

** Σ= Sum Carcinogenic Risk for Metal(loid)s*

DISCUSSION

Pollution in mining areas has drawn attention in several parts of the world, considering that these places are areas with potential risk to human health, due to exposure to chemical substances that are released into the atmosphere and can contaminate different matrices (Müller *et al*. 2021; Ramires *et al*.; 2022). Exposure to human health can occur through different routes of entry, but the inhalation route is the main route of exposure to carcinogenic and non-carcinogenic substances present in the atmosphere (EPA, 2009).

The findings of the present study point to the absence of non-carcinogenic and carcinogenic risks among the trace elements and pollutant gases evaluated, but exhibit Pb and Ni as metals with higher concentrations in PM_{10}. Several studies also highlight the presence of these elements in PM_{10} in mining areas, but not always as elements with higher concentrations (Arregocés *et al*. 2020; Yadav, 2021; Song *et al*. 2015).

Pb is released into the atmosphere mainly by anthropogenic activities and mining activities have a great contribution to this contamination. It is known that the main route of Pb mobility is through the atmosphere, where it is transported by the air and can travel great distances, with larger particles tending to be deposited closer to the emission source, while smaller particles can be deposited at a distance thousands of kilometers (ATSDR, 2020).

The main route of lead exposure is through breathing, where it is deposited in the lower respiratory tract and soon after absorbed (ECHA, 2012). The Candiota region has also been the focus of studies related to Pb contamination, and concentrations of this chemical substance above the maximum levels allowed in Brazilian legislation can be observed in surface waters of the region (da Silva Bonifácio, 2021). In the region, this Pb is present in high concentrations in the urine of children residing in the municipality of Candiota and levels are even higher in those who live less than 2000 meters from a source of pollution (Brum et al, 2022).

In the case of Ni, the largest particles are deposited in the upper respiratory tract, while the smallest ones reach the lower respiratory tract, where they are absorbed by several mechanisms (ATSDR, 2005). After inhalation exposure, about 35% of Ni is absorbed into the bloodstream, being distributed to the lungs, kidneys, skin, brain, among others, but it can also remain in the bloodstream (HSDB, 2005). In the Candiota region, Ni as well as other potentially dangerous elements (Mn and As) can be considered elements that have the greatest contribution to non-carcinogenic risks (HQ) through the inhalation route, with Ni as well as Cr, As, Fe, Pb, Zn and Cu present higher values for the non-carcinogenic risk index the closer to coal mining activities (Ramires *et al*. 2022).

Although metalloids are important toxic constituents in PM_{10}, Brazilian legislation on air quality (CONAMA Resolution 491/2018) includes limits only for Pb in total suspended particles (TSP). Thus, when comparing our findings with international limits (EC, 2014), for the annual average: As (6 ng/m^3), Cd (5 ng/m^3), Pb (0.5 ng/m^3) and Ni (20 ng/m^3) in $PM_{2.5}$, these limits are not were exceeded in the daily values for none of the investigated elements (As, Ni, Pb and Cd), even when compared to $PM_{2.5}$, which would be the most restrictive values in the legislation. In addition to the local absence of maximum permitted limits for these evaluated chemical elements, there are no international limits for Se. However, it is of great importance that the limits for Se are established, because even if it is less toxic than the other elements, coal regions are known to be associated with Se contamination. Recent studies in the Candiota area reveal a health risk for Se (dos Santos et al 2020b), as well as the prevalence of symptoms of Se intoxication in children in the region (dos Santos *et al*. 2020a).

Our study evaluated the seasonal variation of trace element levels in PM_{10} and higher concentrations of Pb, As and Se were found in winter. In turn, the highest levels of Ni and Cd were in the spring. These findings are consistent with other studies, such as the one by Tang & Han (2019), where higher concentrations of metals present in atmospheric dust during winter are observed when compared to other seasons of the year in a city in southeastern China. Pandey et al (2014) also reported that concentrations of particulate matter and gases (SO_2 and NO_2) were highest in the winter season around coal mining areas in India. Luvsan et al (2012) observed that SO_2 pollution in winter was more severe than in other seasons in urbanized areas in Mongolia.

Our study was also concerned with associating air pollution (the concentrations of trace elements linked to PM_{10}, NO_2 and SO_2) with meteorological data. Regardless of the time window (1 to 5 days), temperature showed a negative correlation with most of the evaluated metals. Similar relationships were reported by Radzka (2020), who evaluated the meteorological influence relating to the concentrations of PM_{10} and $PM_{2.5}$ in the air as well as the levels of trace elements in PM_{10}. It can be observed that the content of metals throughout the year was significantly influenced by the month of the year, where Pb and Cd had higher concentrations in the winter months.

It was also observed that air pollution was predominantly affected by air temperature as well as wind speed and humidity, where with increasing temperature the elements As, Cd and Pb decreased in PM10. This fact may be related to the thermal inversion that normally occurs in the winter season, being a natural phenomenon where cold air remains at low altitudes and warm air at higher layers. As a result of this event, pollutants are trapped in the portion of the atmosphere closest to the surface, causing an increase in the concentration of pollutants which can lead to degradation of air quality and consequently harmful effects to human health (Trinh *et al*. 2018).

We can observe that during the sampling period, the levels of pollutants found were between low and moderate, and the non-carcinogenic and carcinogenic risk did not exceed the safety values for health. However, studies indicate the absence of non-carcinogenic and carcinogenic risk when evaluating the exposure routes alone, as well as the contribution of each route associated with different matrices (Müller *et al*. 2021).

Even so, according to Witkowska et al. (2021) it should be taken into account that the population is exposed to a mixture of one or more contaminants, through several exposure routes and through several compartments. Although our study did not show a risk for the inhalation route, mining areas have different trace elements in addition to those evaluated here, such as Cr, Co, Zn, Cu, among others (Arregocés et al., 2020), thus highlighting that the risk for this pathway cannot be neglected, taking into account that studies in the Candiota region have demonstrated risk when evaluated in more than one compartment (dos Santos et al. 2020b; Müller et al. 2021).

The findings of the present study allow a better understanding of the transport mechanisms of atmospheric pollutants related to the influence of meteorological parameters. Although the concentrations of the pollutants investigated here did not exceed the maximum limits allowed in Brazilian and international legislation, nor did they demonstrate non-carcinogenic and carcinogenic risks when evaluated separately, the deficit of maximum limits allowed in the legislation is notorious. Therefore, the research strategy adopted here is of great importance for understanding the risks associated with atmospheric pollutants in coal mining areas in the context of public health, given that over the years the levels of these pollutants tend to increase, investigation and protection measures for these areas are becoming increasingly necessary.

CONCLUSION

Coal mining areas are associated with increased concentrations of atmospheric pollutants. Nevertheless, in our study these pollutants do not present a non-carcinogenic and carcinogenic risk to human health through the inhalation route. Even so, the potential health risk in mining areas should not be overlooked, given that the contribution of other exposure routes along with inhalation can present a high risk. In addition, air monitoring stations are installed approximately 4 km from the exploration areas and there are people living in much closer and potentially more exposed areas. We can also observe that the meteorological data are associated with the concentrations of atmospheric pollutants. Pb and Ni were the trace elements that showed the highest concentration in PM_{10}, followed by Se and Cd. In this sense, it is necessary to include the maximum limits allowed for new elements in Brazilian legislation, thus aiming at improvements in the scope of public health.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Not applicable

CONSENT FOR PUBLICATION

Not applicable

AVAILABILITY OF DATA AND MATERIALS

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

COMPETING INTERESTS

The authors declare that they have no competing interests

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AUTHORS' CONTRIBUTIONS

LCH and FOR were responsible for writing the article, analyzing and interpreting the data. LCH, FOR and FMRSJ were responsible for extracting the data from the databases and preparing the spreadsheets. PA, ALMB and PRMB helped to formulate the key research question and to correct the text. FMRSJ was the advisor and responsible for the research.

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CONFLICTS OF INTEREST

The authors declare no conflicts of financial interest.

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HUMAN HEALTH RISK ASSESSMENT OF AIR POLLUTANTS IN THE LARGEST COAL MINING AREA IN BRAZIL

Laiz Coutelle Honscha[1], Fernanda Oliveira Reis[1], Priscila Aikawa[1], Mariana Vieira Coronas[2], Ana Luíza Muccillo-Baisch[1], Paulo Roberto Martins Baisch[1], Flavio Manoel Rodrigues da Silva Júnior[1]*

[1] Universidade Federal do Rio Grande – FURG, Avenida Itália, km 8, S/N, Campus Carreiros, Rio Grande, RS, Brazil 96203900
[2] Universidade Federal de Santa Maria, Campus de Cachoeira do Sul, Rodovia Taufik Germano, 3013, Passo D'Areia Cachoeira do Sul, Rio Grande do Sul – Brazil 96503-205

*corresponding author – f.m.r.silvajunior@gmail.com + 55 53 32336500

SUPPLEMENTARY MATERIAL

Table S1. Meteorological data obtained from the monitoring station in Bagé through the National Institute of Meteorology (INMET).

Date	Estação do ano	Average					Σ
		Temperature (º C)	Humidity (%)	Pressure (hPa)	Wind speed (m/s)	Wind direction (m/s)	Rain (mm)
Aug, 21	Winter	18.66	71.58	985.33	4.93	96.21	1.00
Aug, 27	Winter	7.28	84.63	997.98	0.15	238.04	2.20
Sept, 02	Winter	19.27	77.21	983.62	1.93	139.83	0
Sept, 08	Winter	19.53	73.50	988.88	0.99	207.00	23.80
Sept, 14	Winter	15.80	89.96	988.22	3.45	120.83	11.80
Sept, 20	Winter	13.47	72.79	986.51	4.19	108.25	0
Sept, 26	Spring	11.44	73.04	996.21	1.43	89.38	0.20
Oct, 02	Spring	12.23	81.08	989.80	1.34	255.13	0
Oct, 08	Spring	16.49	62.29	995.99	4.79	54.17	0
Oct, 14	Spring	18.68	79.67	988.75	1.60	245.46	0
Oct, 20	Spring	21.57	65.79	979.43	4.37	138.42	0
Oct, 26	Spring	16.61	89.29	985.01	2.19	118.04	65.40
Nov, 01	Spring	21.11	75.00	985.12	6.50	45.63	0.60
Nov, 07	Spring	20.29	65.50	990.50	4.76	76.79	0
Nov, 13	Spring	20.19	60.67	991.20	0.86	165.46	0
Nov, 19	Spring	20.70	83.83	983.73	2.37	100.04	16.00
Nov, 25	Spring	24.06	67.71	986.75	3.16	58.67	0
Dec, 01	Spring	21.92	69.04	986.85	3.50	87.13	0
Dec, 07	Spring	21.19	57.29	986.14	0.57	105.29	0
Dec, 13	Spring	22.01	71.50	982.90	1.05	67.17	15.80
Dec, 20	Spring	24.17	70.29	984.14	2.79	106.71	0
Dec, 26	Summer	30.01	50.17	982.53	1.35	178.33	0

Table S2. Correlation between meteorological parameters and atmospheric pollutants for the same day as the collection of air pollutants

	Temperature	Humidity	Pressure	Wind speed	Rain
As	-0.2245	0.1328	-0.1099	0.1182	-0.0753
Cd	0.0989	0.3665	-0.2880	0.0379	**0.7197**
Se	**-0.5017**	0.3830	0.2836	-0.2136	0.2473

Pb	-0.0327	0.3317	-0.0742	0.1560	0.1553
Ni	-0.3097	**0.4568**	-0.0070	-0.0716	**0.5451**
PM_{10}	0.4212	**-0.4616**	-0.2598	-0.1346	**-0.5343**
NO_2	0.2495	-0.1809	-0.1989	**-0.4738**	-0.1209
SO_2	-0.0388	0.3387	-0.0209	-0.0686	0.1847

Table S3. Correlation between meteorological parameters and air pollutants one day before air pollutant collections

	Temperature	**Humidity**	**Pressure**	**Wind speed**	**Rain**
As	-0.2070	**-0.4534**	0.2690	-0.1540	-0.1975
Cd	0.1196	0.1686	-0.0042	-0.0050	-0.1076
Se	**-0.5783**	-0.0199	**0.4753**	0.1201	-0.0819
Pb	0.1802	-0.1582	-0.0768	0.0952	-0.1165
Ni	-0.3126	0.1500	0.3315	0.1252	-0.1308
PM_{10}	0.3805	-0.0737	**-0.4851**	-0.2547	0.2616
NO_2	0.3645	-0.2389	**-0.4566**	-0.0195	0.2775
SO_2	0.2328	0.0117	-0.3323	0.3161	0.4037

Table S4. Correlation between meteorological parameters and air pollutants two days before air pollutant collections

	Temperature	**Humidity**	**Pressure**	**Wind speed**	**Rain**
As	-0.3334	-0.2700	0.3049	0.1830	-0.2804
Cd	0.3279	-0.0900	-0.1848	-0.0022	-0.0752
Se	**-0.4689**	0.2193	0.3747	**0.5769**	-0.1737
Pb	0.3267	**-0.4284**	-0.1885	0.2484	-0.2076
Ni	-0.2375	0.1494	0.3294	0.3209	-0.1781
PM_{10}	0.2142	-0.0373	-0.3074	-0.3765	0.1341
NO_2	0.3336	-0.1946	-0.3527	-0.1809	0.1188
SO_2	0.3468	-0.0995	**-0.4310**	0.0096	-0.1019

Table S5. Correlation between meteorological parameters and air pollutants three days before air pollutant collections

	Temperature	**Humidity**	**Pressure**	**Wind speed**	**Rain**
As	-0.3181	-0.0871	0.1223	0.4225	-0.1783
Cd	0.3600	-0.1010	-0.4081	-0.0628	0.3141
Se	**-0.4722**	0.2992	0.1458	0.4103	0.0763
Pb	0.3257	-0.2533	-0.2669	0.1654	-0.1042
Ni	-0.3062	0.1148	0.2878	0.2635	0.1886
PM_{10}	0.2182	-0.2676	0.0142	-0.2583	0.0239
NO_2	0.2639	-0.2596	-0.0584	0.1268	0.0829
SO_2	0.3594	-0.1339	-0.3486	0.2419	0.3185

Table S6. Correlation between meteorological parameters and air pollutants four days before air pollutant collections

	Temperature	**Humidity**	**Pressure**	**Wind speed**	**Rain**
As	-0.2823	0.0239	0.0648	0.2763	-0.1189
Cd	0.2865	-0.2706	-0.0483	-0.1642	-0.1661
Se	-0.4164	0.0519	0.1396	0.0634	-0.2585
Pb	0.3232	-0.0363	-0.1545	0.2494	-0.0083
Ni	**-0.4574**	-0.1194	**0.5030**	-0.1246	-0.2142
PM_{10}	0.1171	-0.2989	0.0762	-0.0237	-0.0289

NO_2	0.1409	-0.3014	0.0735	0.1213	-0.0735
SO_2	0.2780	-0.1843	-0.1010	0.3667	0.0424

Table S7. Correlation between meteorological parameters and air pollutants five days before air pollutant collections

	Temperature	**Humidity**	**Pressure**	**Wind speed**	**Rain**
As	-0.3994	0.2380	0.1651	0.2260	**0.6235**
Cd	0.2032	-0.0215	-0.1605	-0.2852	0.0684
Se	-0.1881	**0.4338**	-0.3413	0.3760	**0.6356**
Pb	0.1833	0.0854	0.0698	-0.0920	-0.0404
Ni	**-0.4706**	0.1588	0.1613	0.0644	0.2411
PM_{10}	-0.0297	-0.3696	0.3499	-0.1290	-0.3298
NO_2	0.0543	-0.3531	0.1836	-0.1401	-0.1407
SO_2	0.2238	-0.2101	0.0198	-0.1493	-0.0637

6. CONCLUSÃO

Podemos concluir que mesmo não sendo observado um risco não carcinogênico e carcinogênico para as SQIs avaliadas através da via inalatória, o potencial risco à saúde humana não deve ser negligenciado, tendo em vista que a população está exposta a outras substâncias químicas e outras vias de exposição simultaneamente. Assim, podemos observar que existem impactos negativos para a saúde e que a redução destes poluentes na região de estudo é benéfica para a saúde humana, podendo gerar um ganho na expectativa de vida bem como um benefício monetário ao Sistema Único de Saúde.

Contudo, existe a necessidade de rever os limites máximos permitidos no Brasil para os poluentes já existentes na legislação bem como a inclusão de novos limites máximos para poluentes atmosféricos inexistentes. Visando à melhoria da qualidade do ar, no qual está amplamente relacionada não apenas a expectativa de vida da população como também na sua qualidade.