

CHRONIC MANGANESE EXPOSURE THROUGH WELL WATER AND ITS ASSOCIATION WITH NEUROLOGICAL SYMPTOMS IN PADANG, INDONESIA

Azyyati Ridha Alfian^{1,*}, Athifa Midra Nandra¹, Nadifah Khairini Fahdi¹, Fea Firdani¹, and Aria Gusti¹

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Abstract

Heavy metal contamination in groundwater is a major public health issue in Indonesia. Data reveals that roughly 10,683 villages/sub-districts have water contamination, with over 6,000 impacted by residential waste and around 4,500 by industrial waste. This study aimed to assess manganese and lead levels in well water and explore their association with neurotoxic symptoms (motor distractions) in a community in Padang. A cross-sectional survey was conducted among 116 households. Well water samples were tested using Atomic Absorption Spectrophotometry (AAS) and neurotoxic symptoms were assessed via a structured questionnaire. A chi-square test was employed to investigate the correlation between metal concentrations and reported symptoms, uncovering substantial relationships despite constraints in biomarker analysis. 70% of Mn and 47.3% of Pb samples exceeded national standards. A statistically significant association was found between elevated Mn levels and neurotoxic symptoms (OR=3.7; $p=0.032$), while Pb levels showed no significant association ($p=0.4$). Chronic exposure to manganese through well water was linked to increased neurotoxic symptoms. Further research using clinical and biomarker assessments is recommended.

Keywords: Health, Lead, Manganese, Neurotoxic Symptoms, Water

Introduction

The correlation between population growth and density significantly influences the demand for clean water in a specific region. Elevated population density generally necessitates a heightened need for clean water relative to areas with diminished population density. This condition affects access to potable water. In 2021, 10,683 villages/sub-districts in Indonesia experienced issues with water pollution

(Central Bureau of Statistics, 2021). Of these, 6,160 villages/sub-districts encountered water pollution due to residential waste, 4,496 due to industrial waste, and 27 reported contamination from alternative sources. In 2019, 54 out of 98 rivers in Indonesia were classified as moderately to extremely polluted. This situation has worsened since 2018, when 67 of 97 rivers were categorized

*Environmental Health and Occupational Health Department of Public Health Faculty, Andalas University, Padang, Indonesia.
Email: azyyatiridhaalfian@ph.unand.ac.id; athifahmidra@gmail.com; nadhifafahdi@gmail.com; feafirdani@ph.unand.ac.id;
ariagusti@ph.unand.ac.id*

** Corresponding author*

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as lightly polluted, 5 as moderately polluted, and 25 as moderately to extremely polluted (Central Bureau of Statistics, 2020). The predominant drinking water sources in Indonesia are surface water, groundwater, and precipitation. Surface water encompasses rivers and lakes, whereas groundwater consists of shallow wells, deep wells, and springs (Nora *et al.*, 2022). Dug wells serve as the principal water source for several individuals in Indonesia, especially in regions lacking piped drinking water infrastructure. Groundwater is intermittently contaminated, predominantly due to anthropogenic activities such as applying detergents, sulfuric acid emissions, and chemical waste disposal from industrial processes. Pesticides, herbicides, and fertilizers may serve as contaminants, resulting in diminished water quality (Febrina & Ayuna, 2014). Common metal contaminants in well water include lead (Pb), manganese (Mn), iron (Fe), arsenic (As), cadmium (Cd), zinc (Zn), nickel (Ni), and mercury (Hg).

Increased Mn levels in drinking water have been associated with neurological problems, including cognitive deficits and behavioral alterations, particularly in youngsters and the elderly, resulting in symptoms akin to Parkinson's disease. (Zhou *et al.*, 2014; Wasserman *et al.*, 2006; Bouchard *et al.*, 2011). An epidemiological study in Greece indicated that hair samples from residents over 50 who had used drinking water exhibited elevated Mn levels, which may lead to neurological symptoms and heightened Mn buildup in the body (Ashar, 2007; Jasman, 2011). Elevated Mn concentrations (>0.5 mg/L) present hazards of neurological problems, including sleeplessness, lower limb muscle weakness, and face rigidity. Extended exposure may result in diminished speech and impaired locomotion and potentially induce anemia, dermatological issues, and illnesses affecting the heart, liver, blood vessels, and brain. Additional studies demonstrated that Mn-contaminated well water may lead to delayed motor activity, heightened muscular tone, tremors, and psychological disorders (Febrina & Ayuna, 2014; WHO, 2017; Tarigan, 2015). In addition to Mn, the presence of Pb in well water is also a concern. (Ferreira *et al.*, 2022). Principal public health concern of Pb is its significant neurotoxicity. (Tong *et al.*, 2000; Zhang *et al.*, 2023). Significant Pb exposure is linked to consequences including compromised neural development, mortality (predominantly cardiovascular), diminished renal function, and enduring effects resulting in decreased IQ, neurological diseases, and hematological complications such as hypertension (Qadriyah *et al.*, 2019; WHO, 2017). Furthermore, Pb contamination in well water presents significant health hazards, including harm to the central nervous system,

kidneys, and reproductive organs (Wasserman *et al.*, 2006).

The data indicates that Mn concentrations in the Batang Kuranji and Aie Dingin river basins are substantially beyond the acceptable limit of 0.1 mg/L, including measurements at Muaro Panjalingan Bridge (0.29 mg/L), Air Tawar Bridge (0.57 mg/L), and Kelurahan Koto Pulai (0.65 mg/L). The bridge area of Koto Pulai exhibited the highest concentration of Mn. Preliminary observations indicated that this river is utilized for agricultural irrigation, and pesticides are actively applied nearby. A study by Arbi *et al.* (2018) on well water sources adjacent to the Air Dingin dump revealed Pb concentrations of 0.85 mg/L, far beyond the allowable limit of 0.01 mg/L. A preliminary investigation at three sampling locations near the Air Dingin dump revealed that Point I had the greatest Pb concentration at 0.251 mg/L, followed by Point III at 0.195 mg/L and Point II at 0.119 mg/L. These values fail to meet the drinking water quality standards of the Ministry of Health Republic Indonesia Regulation No. 2 of 2023.

Mn and Pb require specific scrutiny relative to other heavy metals due to their unique toxicity characteristics and the insidious yet significant health impacts they may induce, even at minimal doses. Mn and Pb may build in the body, resulting in enduring neurological and developmental harm. Mn and Pb are frequently imperceptible by taste, color, or odor in water, rendering their detection challenging without appropriate testing. (Sarkar *et al.*, 2024). Despite evidence of heavy metal contamination in groundwater, few studies have linked these exposures to health outcomes in Indonesia. Therefore this study aims to examine the association between manganese and lead exposure via well water and neurotoxic symptoms among residents in Padang, Indonesia.

Materials and Methods

This research utilized a quantitative methodology that included a cross-sectional design. The study was conducted in the Koto Tengah District of Padang City, West Sumatra Province, notably in the sub-districts of Koto Pulai and Balai Gadang, from April to September 2024.

a. Study Area and Population

Koto Pulai was primarily an agricultural region, but Balai Gadang was the Air Dingin dump site. The sites were chosen based on data from the Environmental Office of Padang City, which found the greatest Mn and Pb in that area. Koto Pulai was selected to evaluate Mn exposure, comprising a

population of 231 households. In contrast, Balai Gadang, designated as the Air Dingin waste region, was chosen for Pb exposure, having a population of 270 families.

b. Sample

The sample in this study comprised the community that utilized dug wells for drinking water. The sampling was executed by proportionate purposive sampling. The data collection involved primary data acquired by testing well water samples from each household, followed by the analysis of Mn and Pb concentrations at the Health Laboratory Unit of West Sumatra Province. Following the determination of the sample size, 40 households in Kota Pulai were selected for collecting well water samples about Mn exposure. One respondent assessed each residence to evaluate the symptoms of neurotoxicity experienced. The study's inclusion criteria encompassed persons residing in Koto Pulai and Air Dingin Landfill, aged 19 years or older, who utilized well water as their principal daily drinking water source. The exclusion criteria comprised respondents unavailable after three visits and those utilizing piped water, spring water, or alternative sources. Furthermore, to account for confounding variables, participants who utilized several water sources besides well water were removed from the study to establish a causal link between Mn and Pb exposure from well water and neurotoxic symptoms.

c. Data Collection

This study was approved by the Research Ethics Committee of Andalas University, and written informed consent was obtained from all participants. The methodology involves collecting water samples from dug wells belonging to the Koto Pulai community, located at a distance of 0-95 m from the rice field area, with measurements facilitated by Google Earth. The respondents depend on well water for daily consumption, comprising 8 houses in the 1st hamlet, 10 in the 2nd hamlet, 11 in the 3rd hamlet, and 11 in the 4th hamlet, resulting in 40 water samples and 40 respondents. The technique for collecting water samples from wells is known as a grab sample. In the context of Pb exposure assessment at the Balai Gadang and Air Dingin dump, the sample quantity at each location is determined proportionately, considering the topography and elevation of the surrounding residential area near the Air Dingin landfill. The method involves collecting water samples from excavated wells belonging to the Air Dingin landfill community, with the presumption that each household is represented by one individual sampled from its well water to assess symptoms of neurotoxicity. The chosen households are 0-500 m

from the Air Dingin landfill, as determined using Google Earth. The respondents utilize well water for daily consumption, comprising area I (West) with 15 houses, Area II (Southeast) with 15 houses, Area III (East) with 20 houses, and Area IV (North) with 26 houses, totaling 76 houses and 76 individuals reliant on well water. The well water sampling technique is conducted using grab samples. Water samples for Mn and Pb were collected using a measuring apparatus designed for chemical analysis, specifically a 100 ml sample vial. Water samples were examined utilizing the Atomic Absorption Spectrophotometer (AAS) based on Indonesian National Standard SNI-6989.8:2009 for analytical methods used to determine Mn and Pb content. The initial step involves introducing 50 ml of the sample into a 50 ml Erlenmeyer flask, adding 5 ml of 65% HNO₃, and heating until nearly dry, leaving approximately 15-20 ml left over. Evaporate and chill. The residual solution is transferred into a 50 ml volumetric flask via filter paper, and aquabidest is added to the calibration mark and mixed thoroughly. Subsequently, the solution is transferred into a vial that has been washed with aquabidest and is suitable for analysis via AAS. Laboratory technicians calibrated and validated the analytical instruments; hence, the researcher lacked comprehensive knowledge of the exact technical processes employed. Environmental settings were regulated to avert contamination and other variables that could influence the research outcomes.

The tool for evaluating neurotoxic symptoms was a questionnaire derived from a prior study (Noviandi, 2012), with the symptoms assessed by a medical professional through interview and checklist including 15 items related to motor and cognitive functions. The observed symptoms encompassed bodily rigidity, tremors, ambulation difficulties, reduced mobility, challenges in writing and speaking, involuntary salivation, difficulties in sitting down or rising from a chair, and abrupt involuntary body movements. Each respondent who reported experiencing 3 out of 15 symptoms is categorized as a respondent with neurotoxic symptoms. The questionnaire also encompassed data on body weight, daily water intake, gender, and duration of exposure to well water.

d. Data Analysis

The test findings were evaluated against the allowable water quality criteria established by the Ministry of Health Republic Indonesia Regulation No. 2 of 2023, which stipulates maximum limits of 0.1 mg/L for Mn and 0.01 mg/L for Pb. (Menteri Kesehatan Republik Indonesia, 2023). Water samples that surpass the specified limit are deemed non-compliant with the criteria. Assessments of

well water parameters and interviews utilizing questionnaires were undertaken to detect and quantify respondents' neurological problems. The participants chosen for this study were above 19 years of age, and data were collected on anthropometric measures, water consumption habits, and exercise patterns. Secondary data were collected from documents and records pertinent to the research requirements, including demographic statistics and the count of homes utilizing well water for everyday activities. Data processing procedures encompassed editing, coding, data entry, and cleansing. Data analysis techniques encompassed Univariate Analysis, detailing the frequency distribution of Mn and Pb concentrations and classifying them as compliant or non-compliant with the standards set forth by the Ministry of Health Republic Indonesia Regulation No. 2 of 2023, as well as delineating the neurotoxic symptoms experienced by respondents, categorized into those exhibiting symptoms and those without. Every respondent reporting 3 out of 15 neurotoxicity symptoms within the symptomatic group. (Noviandi, 2012). Bivariate analysis was performed utilizing the chi-square test at a significance level (α) of 0.05 and a 95% confidence interval (CI) to ascertain the statistically significant link between Mn and Pb concentrations in well water and neurotoxicity symptoms. This study also did not carry out multivariate analysis due to an insufficient sample size. This study has drawbacks; it is not feasible to conduct medical measures and assess biomarkers of Mn and Pb concentration in the respondents' blood, and neurotoxicity symptoms are solely evaluated by an anamnesis questionnaire due to financial constraints (Arbi *et al.*, 2018).

Results and Discussion

a. Results

The research findings indicate the concentrations of Mn and Pb in well water, as presented in Table 1, derived from two distinct locations: Koto Pulai, with 40 water samples from

households and respondents for Mn concentration, and Balai Gadang, encompassing 76 water samples from households and respondents in the vicinity of the Air Dingin landfill area. The classification in Table 1 adheres to the rules established in the Ministry of Health Republic Indonesia Regulation No. 2 of 2023, which specifies the maximum permissible quantities of Mn and Pb in water.

Table 1. Distribution of Mn and Pb in Well Water

	Category		Total
	Non-Compliant	Compliant	
Mn Concentration	28 (70%)	12 (30%)	40 (100%)
Pb Concentration	36 (47.3%)	40 (52.7%)	76 (100%)

According to Regulation No. 2 of 2023 by the Ministry of Health of the Republic of Indonesia, the maximum permissible concentration for Mn is 0.1 mg/L, and for Pb is 0.01 mg/L in water. However, as indicated in Table 1, approximately 70% of the community's water wells fail to comply with the Mn standard (> 0.1 mg/L), and 47.3% exceed the Pb threshold (> 0.01 mg/L). Table 2 summarizes the concentrations of Mn and Pb in the respondents' well water. The research results indicate the concentrations of Mn and Pb in the water.

Table 2. Details Concentration of Mn and Pb in Well Water

	Mn Concentration	Pb Concentration
Max	2.818	0.349
Min	0.000	0.000
Mean	0.165	0.182
Standard	0.1	0.01

Table 2 indicated that the maximum concentrations identified in the study are 0.208 for Mn and 0.349 for Pb. The average concentration of Mn and Pb is 0.165 and 0.182, respectively. According to Regulation No. 2 of 2023 by the Ministry of Health of the Republic of Indonesia, the average concentrations of Mn and Pb observed in the study exceeded the allowable threshold levels. The neurotoxic symptoms observed in the population are detailed in Table 3.

Table 3. Relationship Between Mn and Pb Concentrations and Neurotoxic Symptoms

Concentration	Symptoms			p-value	POR (CI 95%)
	Neurotoxic Symptoms	No Neurotoxic Symptoms	Total		
Mn					
Non-Compliant	19 (47.5%)	9 (22.5%)	28 (70%)	0.032	3.7 (1.63 - 11.56)
Compliant	3 (7.5%)	9 (22.5%)	12 (30%)		
Total	22 (55%)	18 (45%)	40 (100%)		
Pb					
Non-Compliant	7 (9.2%)	29 (38.1%)	36 (47.3%)	0.4	0.895 (0.740- 1.083)
Compliant	4 (5.3%)	36 (47.4%)	40 (52.7%)		
Total	11 (14.5%)	65 (85.5%)	76 (100%)		

Based on Table 1 and Table 3 shows that among 40 respondents with manganese exposure, 70% had well water levels above the national standard of 0.1 mg/L. These individuals were 3.7 times more likely to report neurotoxic symptoms than those with compliant Mn levels ($p = 0.032$). In contrast, Pb exposure above the threshold was observed in 47.3% of participants, but showed no significant association with symptoms ($p = 0.4$). The limitation in this research is that it cannot conduct multivariate adjustments due to small sample size. Figure 1, displays the neurotoxic symptoms reported by each respondent.

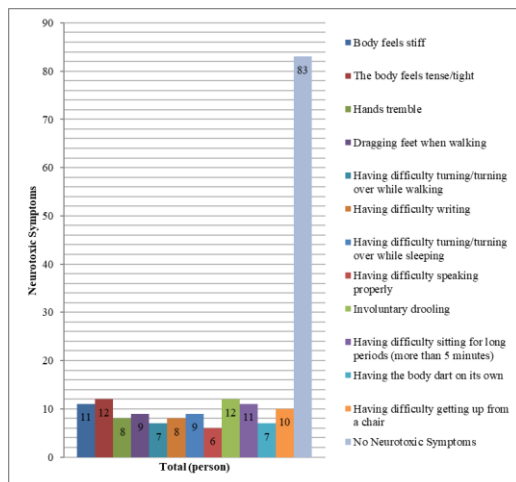


Figure 1. Distribution of Neurotoxic Symptoms and no Neurotoxic Symptoms

The findings revealed that most respondents reside in proximity to rice fields. The distribution of well types and conditions indicates that around 85.7% of respondents utilize dug wells. A predominant 74.3% are closed. The water quality assessment, categorized by well type and construction, reveals that the maximum concentration of Mn is 2.818 mg/l, detected in a dug well with a closed structure in the 1st hamlet area, adjacent to a rice field, merely 5 meters away. The water treatment at this sampling location employed a basic filtration technique. Mn values of 1.080 mg/L and 0.458 mg/L were detected in open wells exhibiting brownish-colored water at the second hamlet.

b. Discussion

Numerous studies have documented elevated levels of Mn in agricultural water sources, especially in regions characterized by intensive farming and acidic soils. Agricultural practices, including applying fertilizers and pesticides, can modify soil chemistry and facilitate the leaching of naturally existing Mn from the soil into

groundwater. (Misa *et al.*, 2019; Sunarto, 2021; Cheng *et al.*, 2022). A study in Margaasih, Bandung, also reported higher Mn levels in irrigation water and soils, attributed to natural geological conditions and extended agricultural runoff. (Supandi, 2022) These findings underscore that Mn contamination of farming settings can be intensified by natural soil composition and human activities, necessitating the monitoring and managing of water quality in farming areas to safeguard environmental and public health.

Based on Figure 1, respondents' most frequently reported health symptoms were involuntary drooling, body stiffness, whereas the least frequently reported symptoms included hand tremors and difficulties dragging the feet while ambulating. Each respondent has been utilizing the water for an average of 25 years. Statistical testing yielded significant results, with a p -value of 0.032. The risk value suggests that individuals consuming drinking water with Mn concentrations above quality requirements are 3.7 times more likely to exhibit neurotoxic symptoms. In the human body, trace levels of Mn are not detrimental to health; nevertheless, excessive quantities can accumulate in the liver and kidneys. Opinions regarding the health implications of Mn poisoning vary; nevertheless, chronic exposure is generally associated with neurological diseases and symptoms akin to Parkinson's disease. High amounts of Mn exposure lead to the accumulation of Mn concentrations, impacting the body's metabolism. Consequently, the likelihood of encountering adverse effects, including Parkinsonian syndrome, escalates. Prolonged exposure to Mn can result in symptoms akin to Parkinson's disease, a condition referred to as manganism. Mn accumulates in brain regions, including the globus pallidus and substantia nigra, which are implicated in motor regulation and have a high density of dopaminergic neurons. This accumulation causes oxidative stress, mitochondrial malfunction, and neuroinflammation, all leading to the death of dopaminergic cells. The neurotoxicity of Mn is mainly due to its capacity to produce reactive oxygen species (ROS), resulting in oxidative stress. Mn impairs mitochondrial activity by blocking the complexes of the electron transport chain, leading to reduced ATP synthesis and elevated reactive oxygen species production. Moreover, Mn exposure diminishes cellular antioxidants such as glutathione, intensifying oxidative damage. Oxidative stress promotes inflammatory pathways, including the NF- κ B and NLRP3 inflammasome pathways, leading to neuroinflammation and neuronal damage. In addition to oxidative damage and inflammation, Mn disrupts neurotransmitter systems, especially the

dopaminergic system. It hinders dopamine metabolism and interferes with synaptic vesicle function by impacting proteins such as α -synuclein, resulting in synaptic dysfunction. Mn also disrupts calcium homeostasis and increases endoplasmic reticulum stress, further jeopardizing neuronal health. These complex disturbances result in the motor and psychological symptoms typical of manganism. Comprehending these pathways is essential for formulating viable therapeutic strategies to alleviate Mn-induced neurotoxicity (Yu *et al.*, 2022; Chen *et al.*, 2021; Li *et al.*, 2022; Fernandes & Zheng, 2023). Mn can also hinder autophagy, a cellular mechanism that eliminates damaged proteins, resulting in the buildup of α -synuclein, a key protein linked to Parkinson's disease. The interplay between Mn exposure and genetic or epigenetic variables heightens an individual's vulnerability to Parkinsonian symptoms (Burton & Guilarte, 2009; Guilarte, 2013; Peres *et al.*, 2016). Studies in both animal models and humans have demonstrated that Mn can interfere with dopamine metabolism, impact gene expression via epigenetic mechanisms, and alter the lipid composition of neurons, substantiating the environmental influence on the onset of Parkinsonism. The findings indicate that responders displaying neurotoxic symptoms akin to those of Parkinson's disease had undergone prolonged exposure to Mn for 25 years or had experienced chronic exposure (Sriram *et al.*, 2010; Hartini, 2012; Sidoryk-Wegrzynowicz & Aschner, 2013; Tarigan, 2015). Mn levels in natural water systems are often below 0.1 mg/L. When concentrations beyond 0.1 mg/L, ordinary treatment procedures may be inadequate in lowering them to the permissible limit for drinking water, necessitating specialized treatment. Oxidation is the most generally used method to remove Mn from water, followed by separating suspended particulates. Mn is more oxidation-resistant than iron because of its slower oxidation rate. The authorities of Padang City should inform the population about the significance of clean water and methods for maintaining water quality at home. They should also offer instruction on fundamental domestic water treatment methods, including filters and boiling water. Support should be provided for implementing effective and efficient water treatment technology, such as basic water filters, ultraviolet disinfection systems, or chlorination methods. Engage the corporate sector and non-governmental organizations in programs for drinking water purification, encompassing technology, money, and education. Residents in Koto Pulai are advised to utilize alternative drinking water sources, such as refilled stations. Water should be treated at home before use, for instance,

by boiling it for a minimum of 1-3 minutes and employing water filters to eliminate particles and contaminants. Furthermore, the filter utilized is appropriate for the types of pollutants present in the water.

Table 2 indicates that, alongside Mn exposure, Pb exposure surpasses quality norms, with 9.2% of respondents utilizing non-compliant water sources exhibiting neurotoxic symptoms. The maximum Pb concentration in this study was 0.350 mg/L. The identification of elevated Pb contents in specific households is ascribed to the proximity of leachate to community wells and the interactions between water and Pb present in pipes or painted water storage tanks. Interviews with inhabitants in several research sites, including the 3rd hamlet, indicate that well water conditions deteriorate and become turbid following severe rains. Moreover, livestock farms are situated near the people's residences, which may elevate Pb concentrations in the environment, potentially leading to water contamination. The Air Dingin landfill employs an open dumping technique, receiving a rubbish influx of 640 tons daily. Waste susceptible to chemical degradation can seep into liquids referred to as leachate. At the Air Dingin landfill, leachate is gathered in a pond for treatment and quality assessment to ensure compliance with permissible limits. Solid trash at the disposal location may contain Pb, posing a risk of environmental contamination. This is further corroborated by the open dumping method, wherein garbage accumulates without specialized treatment, resulting in ecological disruptions. This approach may induce contamination of adjacent water sources. Leachate infiltrates the soil during precipitation and has the potential to pollute the wells. This aligns with a study by Heny (2022), which discovered that Pb contamination originates from rainwater infiltrating waste piles, resulting in leachate formation. Leachate is categorized as a harmful environmental contaminant. Leachate accumulation in the soil might result in environmental contamination surrounding the disposal site (Tumanggor *et al.*, 2012; Heny *et al.*, 2022). In alignment with other prior studies indicating Pb pollution from groundwater, Cheng *et al.* (2022) examined Pb concentrations near the Kaliori dump by analyzing three water samples from homeowners' drilled wells. The findings indicated that well 1, located approximately 100 meters away, exhibited a concentration of 0.061 mg/L; well 2, around 135 meters away, displayed 0.052 mg/L; and well 3, positioned at approximately 110 meters, recorded 0.047 mg/L. A study conducted by Siswoyo and Habibi (2018) examined Pb concentrations in well water surrounding the Wukirsari dump in Gunung Kidul, revealing that the

Pb concentration surpassed the quality limit, measuring 0.55 mg/L. A study by Besnaya (2019) further corroborated this by measuring Pb concentration in shallow well water in the Payakumbuh landfill, situated within a 300-meter radius of residential neighborhoods. The study identified a Pb concentration of 0.971 mg/L in the input pipes, which exhibited elevated water parameters. The results are further validated by the survey conducted by Handriyani *et al.* (2020) at the Banjar Suwung Batan landfill in South Denpasar. The study revealed that Pb contents in excavated well water samples varied from 0.0060 mg/L to 0.1023 mg/L (Siswoyo & Habibi, 2018; Besnaya, 2019; Handriyani *et al.*, 2020).

Pb exposure assessed at the Air Dingin landfill indicated no significant correlation between Pb concentration and neurotoxic symptoms, as evidenced by a p-value of 0.4 because the dose of consumption is low compared to the respondent's body weight. This study indicates that the average body weight category was roughly 58.87 kg, implying that this weight does not present a substantial health risk. Ashar (2007) posits that in risk analysis, body weight affects risk value; hypothetically, an increase in body weight correlates with a reduced probability of health issues. Prolonged exposure to Pb in the body may lead to anemia and inflict harm on the central nervous system (CNS) and peripheral nervous system (PNS). CNS injury frequently impacts youngsters, hindering their cognitive development, whereas PNS damage generally arises in adults following extended exposure.

Pb exposure is becoming acknowledged as a substantial environmental risk factor for Parkinson's disease. Epidemiological studies indicate that persons with more cumulative Pb exposure, especially those with increased Pb concentrations in bone tissue, had roughly double the risk of getting Parkinson's disease compared to those with lower exposure levels. The neurotoxicity of Pb is chiefly due to its capacity to imitate calcium ions, facilitating its passage across the blood-brain barrier and its accumulation in neurons and glial cells. Upon entry, Pb interferes with calcium-dependent signaling pathways, resulting in compromised neurotransmitter release and absorption, especially dopamine, which is essential for motor function. This disturbance leads to dopaminergic dysfunction, a characteristic of Parkinson's disease. At the cellular level, Pb produces oxidative stress by producing ROS, which harms biological components, including lipids, proteins, and DNA. Pb also disrupts mitochondrial function and activates protein kinase C, generating increased reactive oxygen species and neuronal

death. Moreover, Pb exposure has been associated with the buildup of α -synuclein, a protein that constitutes Lewy bodies in Parkinson's disease patients, indicating a possible involvement in the disease's development. These methods emphasize the intricate relationship between environmental contaminants and neurodegenerative disorders, underscoring the necessity of reducing Pb exposure to diminish Parkinson's disease risk (Dribben *et al.*, 2011; Caudle *et al.*, 2012; Ullah *et al.*, 2021; Pyatha *et al.*, 2022; Shvachiy *et al.*, 2023). A study comprising 330 Parkinson's disease patients and 308 controls revealed that persons in the highest quartile of tibial Pb concentration exhibited about a threefold greater risk of Parkinson's disease compared to those in the lowest quartile. However, this study does not correspond with the data obtained (Weisskopf *et al.*, 2010). Although multiple studies have demonstrated a definitive correlation between Pb exposure and neurotoxic effects, specific research has failed to identify substantial neurological symptoms despite the presence of quantifiable Pb levels. A study involving rats exposed to low amounts of Pb during development revealed no significant changes in body weight or apparent neurological abnormalities between the exposed and control groups. Despite observing biochemical abnormalities, including modifications in nitric oxide synthase activity and NMDA receptor expression in the hippocampus, these did not result in apparent behavioral or neurological deficits. A prospective study of battery plant workers indicated that, despite increased blood Pb levels, there were no significant alterations in nerve conduction velocities or other clinical signs during two years. It suggests that Pb may not elicit immediate or apparent neurotoxic consequences at specific exposure levels. Nonetheless, it is crucial to acknowledge that these findings do not indicate that Pb exposure is innocuous; instead, they underscore the intricacy of neurotoxic effects and the necessity for additional study to elucidate the thresholds and mechanisms involved (Seppäläinen *et al.*, 1983; WHO, 1977; Zhu *et al.*, 2005; Ashar, 2007; Musrawati, 2016). Reducing Pb contamination in water, especially near waste sites, necessitates a blend of preventive and remedial techniques. It entails installing appropriate leachate collection and treatment systems to avert Pb infiltration into groundwater or surface water. Advanced filtering technologies, including reverse osmosis, ion exchange, and adsorption with activated carbon or biochar, can eliminate Pb from contaminated water sources. Consistent water quality surveillance is crucial for the early detection of Pb concentrations, and vegetative buffer zones can aid in the absorption and filtration of runoff. Furthermore, adopting

stringent landfill management protocols and using impermeable liners can reduce Pb leakage from solid waste.

This study is robust in emphasizing public health concerns, specifically with exposure to Mn and Pb in water and their correlation with neurotoxic symptoms observed in the community. The findings demonstrate a substantial correlation between Mn concentrations surpassing conventional thresholds and the manifestation of neurotoxic symptoms. Nonetheless, the cross-sectional form of this study-characterized by measures gathered at a singular moment-restricts the capacity to derive robust causal inferences. A key limitation was the lack of biomarker measurements in participants, namely the concentrations of Pb and Mn accumulating in blood or other organs. Consequently, causal linkages were evaluated exclusively through self-reported symptoms from participants. Therefore, subsequent research should employ a more rigorous study design, incorporating direct measurement of Mn and Pb quantities accumulated in people's bodies, to more effectively prove causality.

Conclusions

This study found that manganese concentrations in well water exceeding national standards were significantly associated with self-reported neurotoxic symptoms, whereas no such association was found for lead. The cross-sectional design and absence of biomarker analysis limit causal interpretation. Nevertheless, the findings highlight the need for improved monitoring of manganese in rural water supplies and further longitudinal studies using clinical and biological outcome measures.

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