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Disparities in potential nitrate exposures within Iowa public water systems†

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Nitrates (measured as nitrate-nitrogen) in drinking water exceeding the maximum contaminant level (MCL) of 10 mg L^{-1} can cause significant health risks, such as methemoglobinemia. Even long-term exposure to concentrations below the MCL can also increase the risks of cancer. Iowa, a major agricultural producer, has grappled with decades-long nitrate pollution in its water systems due to intensive farming practices and animal feeding operations. To help in developing interventions and policies to protect public health, this study delves into long-term nitrate levels in 871 Iowa public water systems (PWSs) between 2012 and 2022 and examines sociodemographic disparities in potential nitrate exposure in drinking water. Average nitrate concentration in Iowa's PWSs increased between 2012 and 2016, reaching an average peak of 3 mg L^{-1} in 2016. 2.5% of 871 PWSs are classified as 'high-risk', with nitrate concentrations consistently exceeding 5 mg L^{-1} over the study period, primarily in eastern and western Iowa, where animal feeding operations are concentrated. The absence of nitrate removal processes at these PWSs contributes to the sustained elevated levels. On average, 7.4% of the state's population served by PWSs has been exposed to nitrate levels consistently exceeding 5 mg L^{-1} in the past decade. Disparities exist among various sociodemographic groups, with statistically significant higher exposure rates (10.1%, 9.6%, 9.2%, and 8.7%) observed for people whose incomes are below the federal poverty threshold ($26 496/year), older adults (65 years and above), people of colour, and children (5 years and younger). These disparities are particularly concerning as these populations often lack the resources to address the consequences of water contamination. Our study highlights inequities in Iowa's PWSs concerning potential nitrate exposures and underscores a need for nitrate remediation in specific areas. Addressing these disparities is crucial to safeguarding the health of vulnerable populations and promoting environmental justice in water management.

Water impact

The study investigates the long-term trends in nitrate concentrations in Iowa's public water systems over the period of 2012 to 2022, with a focus on identifying sociodemographic disparities in potential exposure to nitrates in drinking water. The findings highlight an urgent need for targeted public health interventions and policies to address nitrate contamination in vulnerable communities. By providing a localized analysis of water quality, this study advances the understanding of environmental justice issues, building upon and refining previous research in the field.

Introduction

Nitrate (NO_3^-) is a compound commonly found in fertilizers, animal manures, and wastewater sewage.[1] Nitrate originating from agricultural activities, industrial discharges, and wastewater treatment processes can contaminate drinking water sources such as groundwater and surface water bodies. In the United States, the Safe Drinking Water Act (SDWA) establishes a maximum contamination level (MCL) for nitrate at 10 mg L^{-1} NO_3-N in drinking water. This regulation is

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implemented due to the adverse health effects of elevated nitrate exposure,[1] including methemoglobinemia in infants, commonly known as "blue baby syndrome". This condition reduces the blood's oxygen-carrying capacity, leading to cyanosis and potential life-threatening complications.[2,3] Extended exposure to nitrate levels below the MCL in drinking water can still have adverse effects on health, potentially increasing the risks of preterm birth,[4] birth defects,[4–6] and various types of cancer.[2,7–17]

High levels of nitrate have been found in surface and groundwater drinking water sources across the United States,[18,19] notably in regions characterized by intensive farming and animal production. As the primary producer of corn and swine in the U.S., Iowa faces challenges in managing nutrient levels in the environment.[20,21] Average

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Environ. Sci.: Water Res. Technol., 2025, **11**, 959–971 | **959**

nitrate concentrations in Iowa's drinking water increased between 2003 and 2017, with a concentration averaged across 236 towns reaching as high as 5 mg L^{-1} NO$_3$–N.[19] Nearly half of the water samples taken from streams in heavily farmed areas in eastern Iowa had nitrate levels surpassing the MCL.[1] However, only 4% of the PWSs across the state have some form of nitrate treatment, including anion exchange, reverse osmosis, and blending (see ESI†). These facilities require substantial capital investment and have high operational cost,[22,23] making them inaccessible for many small and low-resourced communities across the state. Although the current MCL for nitrate, set at 10 mg L^{-1} as nitrogen (N), aligns with the maximum contaminant level goal set by the EPA, emerging research and ongoing assessments have raised questions about whether this regulatory limit adequately protects all population groups, particularly sensitive groups such as postmenopausal women, infants, and pregnant individuals.[24] Recent studies have suggested potential health effects at concentrations below the current MCL, underscoring the need for a closer examination of low-level exposures.[12,15,17,25,26] The ongoing Integrated Risk Information System (IRIS) assessment by the EPA provides a critical framework for assessing nitrate exposure from drinking water separately from food, particularly among vulnerable populations. This assessment calls out the need to revisit health impacts of nitrate in water using updated scientific methodologies.[24]

Vulnerable populations can be exposed to the risks from high nitrate concentrations in public water supplies, turning what should be a basic human right—clean drinking water —into a hidden health hazard.[27] Communities of color, families with low income, and residents of certain geographic regions disproportionately bear the brunt of inadequate water services[28–35] including exposure to contaminants, insufficient infrastructure for clean water access, and financial barriers to securing adequate water services. In the San Joaquin Valley of California, community water systems serving larger percentages of Latinx populations had drinking water with higher nitrate levels, particularly in smaller water systems,[36] and people of colour were associated with a 31% increase in the likelihood of elevated nitrate levels.[37] These issues often stem from systemic socio-economic inequalities and historical neglect.[34,38–41] A nationwide study revealed that 5.6 million Americans are served by a water system that had an average nitrate concentration of at least 5 mg L^{-1} NO$_3$–N.[42] In particular, water systems serving communities in the top quartile for Hispanic population exceeded 5 mg L^{-1} nearly three times as often as those serving the lowest quartile.[42] In the Midwest, particularly in the agricultural regions of Iowa, Minnesota, and Wisconsin, areas where drinking water shows elevated levels of nitrate frequently align with communities whose median household incomes fall below the state's median.[43]

Although many studies have investigated nitrate exposure disparities across sociodemographic groups, these investigations often lack the spatial granularity required, such as at the utility level, to inform effective decision-making relevant to affected communities. This knowledge gap is characterized by a lack of comprehensive analysis of long-term nitrate levels in finished water from individual drinking water treatment plants, as well as inadequate information on the sociodemographic characteristics of the population served by each treatment plant. In this paper, we addressed this gap by aggregating and analyzing data for active Iowa public water systems (PWSs). Specifically, we analyzed long-term trends of average nitrate levels in finished water from PWSs in Iowa, identified 'hotspots' or high-risk facilities, and explored sociodemographic disparities related to potential nitrate exposures (Fig. 1). Our study reveals decade-old nitrate issues in Iowa's drinking water, highlights inequities concerning potential nitrate exposures, and underscores the need for nitrate remediation in specific areas. This research is especially relevant because Iowa's PWSs serve a multitude of small communities that face challenges related to funding, maintenance, and protecting public health and the environment.[38,41] Findings from this paper can help local water managers and regulatory agencies prioritize efforts, while emphasizing considerations of equity and justice in decision-making processes.

Methods

Data description and preliminary processing

A PWS is defined as a public utility that provides potable water for consumption and domestic usage to residents.[44] Such a system must either have a minimum of 15 service connections or cater to an average daily population of at least 25 individuals for at least 60 days per year. We obtained data on Iowa's PWSs from three sources: the U.S. Environmental Protection Agency's (EPA's) Safe Drinking Water Information System (SDWIS), Iowa Department of Natural Resources (IDNR), and EPA's Enforcement and Compliance History Online (ECHO).

SDWIS provides PWS characteristics including system name, activity status, system type (community, non-community, etc.), number of people served, source water type (groundwater or surface water), and region served by the system (county), start and end dates of the tests and results (i.e., air quality, toxicity, lead, and copper). PWSs are grouped using EPA's classification of system size: very small (serving ≤500 people), small (serving 501–3300 people), medium (serving 3301–10 000 people), large (serving 10 001–100 000 people), and very large (serving >100 000 people).[44] We compiled PWS characteristics records for a total of 1076 active PWSs in Iowa.

Through collaboration with IDNR, we also acquired the reported annual nitrate concentration (NO$_3$–N mg L^{-1}) data for finished water from each PWS in Iowa, spanning the period from 2012 to 2022. These data were collected by the PWSs as mandated components of compliance monitoring and reported to state regulatory authorities (e.g., IDNR) in
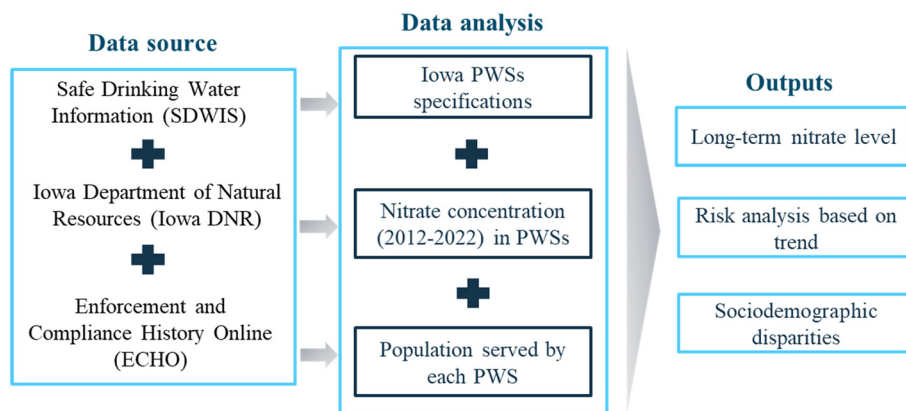
Fig. 1 Flowchart summarizing the approach used in this study.

adherence to the requirements outlined in the SDWA. We refined the dataset by selecting active community water systems (a subclass of PWS, characterized by its year-round service to residential areas[44]) that reported nitrate data, resulting in a final set of 871 PWSs and a total of 21 198 nitrate records. Not every PWS has a complete 10-year record of reported nitrate data. Detailed selection criteria are described in the (ESI†). We also obtained information about nitrate treatment technologies used at PWSs from IDNR. This data contains records for 31 PWSs including information such as name and identification code of the system, its classification as a community-based system, the source of the water supply, the population it serves, and the specific treatment methods employed.

Lastly, we sourced sociodemographic information linked to each PWS from the EPA's ECHO database. This dataset includes the percentage of the population (as of 2016–2020 American Community Survey (ACS) 5-Year Summary) within a 5-mile radius of each PWS with specific characteristics, namely individuals with low income (less than or equal to twice the poverty level), people of colour, children aged 5 years and younger, and individuals aged 65 years and older. We associated this information with each PWS in Iowa and assumed that the sociodemographic profile within a 5-mile radius of the PWS represents the overall population served by that PWS This decision was driven by both data availability and practical considerations because the EPA's ECHO database provides sociodemographic information for radius of 1, 3, and 5 miles around each PWS. Our assumption may impose limitations because factors such as urban–rural variations, demographic clusters, and community dynamics can influence the diversity within the entire service area of the PWS. We validated the assumption by, comparing the percentage distribution of each sociodemographic category within a 5-mile radius of all PWSs in each county with the corresponding percentage within the entire county in the year 2016–2020. The comparison suggested slight overestimation for sociodemographic characteristics within the county (Fig. S1†). However, we believe that our approach can still provide a good approximation of the sociodemographic

characteristics served by each PWS due to the historical pattern in which water treatment plants were often constructed near marginalized communities.[38,45]

We cross-checked data from the three sources and implemented data cleaning and quality assurance protocols (see ESI†). As a result, we generated a comprehensive dataset encompassing 871 PWSs in Iowa, or 80.9% of all PWSs. The 871 PWSs are representative of the entire 1076 PWSs in Iowa (Fig. S2†). This dataset includes the following key information: system name, system size, geographic location (e.g., latitude, longitude), county, population served, source water type, annual average nitrate concentrations from 2012 to 2022, existing nitrate treatment technology, and percentage of population with specific sociodemographic classification. Of the 871 PWSs included in our dataset, only 28 PWSs utilize surface water as their primary source. Therefore, we do not anticipate significant seasonality in nitrate levels due to hydrologic variability (i.e., precipitation). In addition to analysing results at the individual PWS level, we also analysed results at the geographic division established by the Iowa Department of Public Health, known as the Regional Medical Coordination Centres (RMCCs) for COVID-19 monitoring (Fig. S3†). Challenges with the dataset refinement and processing are described in ESI† - dataset refinement process.

Nitrate exposure assessment for Iowa PWSs

Taking annual mean nitrate concentration for each of the 871 PWSs between 2012 and 2022, we classified nitrate concentrations C into four categories in accordance with scholarly literature:[4,25,26,46–48] $C \leq 1$ mg L^{-1}, 1 mg L$^{-1} < C \leq 3$ mg L^{-1}, 3 mg L$^{-1} < C \leq 5$ mg L^{-1}, and $C > 5$ mg L^{-1}. The regulatory limit for nitrate in public drinking water supplies (10 mg L^{-1}) aims to safeguard against infant methemoglobinemia. We adopted 5 mg L^{-1} as a threshold for elevated concentration because there is strong epidemiological evidence linking drinking water nitrate ingestion to adverse health outcomes at 5 mg L^{-1}.[12,15,17,25,26] Additionally, nitrate concentrations as low as 2–3 mg L^{-1} can

exacerbate lead corrosion in plumbing systems containing lead-tin solder, potentially leading to the release of lead-bearing particulates into the water supply.[49] Therefore, it is also important to evaluate the implications of nitrate concentrations below 5 mg L^{-1}.

We analysed the trends of annual average nitrate concentration for each PWS using linear regression. A positive slope of the regression line for PWS indicates an upward trend. We also characterized each PWS into high, medium, or low risk based on whether the annual nitrate concentrations consistently exceeded the 5 mg L^{-1} threshold between 2012 and 2022. High-risk systems were characterized by average nitrate concentration consistently exceeding 5 mg L^{-1}. In contrast, systems with an average concentration consistently below 5 mg L^{-1} over the decade were classified as low risk. Medium-risk systems were defined as those without exhibiting a consistent trend above or below the 5 mg L^{-1} threshold.[50] In analysing the potential disparity among socio-demographic groups, we adopted the use of quantile method in ArcGIS. Using the quantile method for colour shading on these maps provides a more effective way to communicate geographic patterns and trends in the data by enhancing pattern detection.[51,52] The quantile method focuses on relative ranking rather than absolute values. This is particularly valuable when comparing variables with wide-ranging scales, such as income levels or age demographics alongside nitrate levels. Focusing on relative standing rather than exact numbers (*i.e.*, quantiles place data points into categories that represent their position relative to the rest of the data instead of using fixed value ranges) allows clearer comparisons across demographic groups without letting extreme values distort the visual interpretation.[53] Finally, the quantile method enhances differentiation within closely grouped data because average nitrate concentration data can often be skewed, with most counties clustering at lower levels and only a few at higher levels.[54,55] By grouping counties with
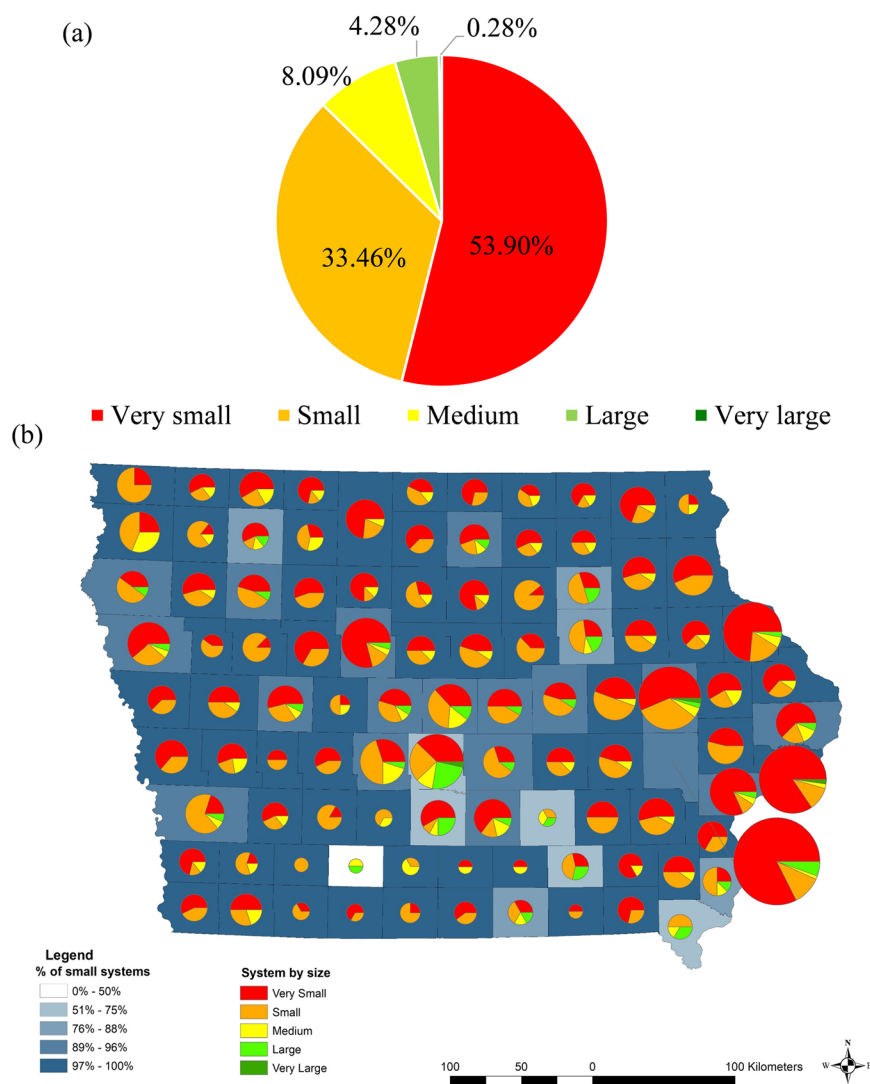

Fig. 2 Classification of Iowa public water systems by size: (a) classification for all 1076 PWSs considered. (b) Classification at the county level. Size of pie indicates total number of PWSs within the county.% of small systems encompasses "very small", "small", and "medium" as defined by EPA.[44]

similar rankings, the quantile approach accentuates colour variation, making it easier to spot geographic "hotspots" without overemphasizing small differences. These advantages make quantile-based shading an ideal choice for effectively conveying both demographic and environmental patterns on these maps.

Results and discussion

Overview of Iowa's PWSs

Iowa's primary water source is groundwater, with 74% of PWSs providing treated groundwater to homes. In contrast, 140 (16%) PWSs supply water from surface sources, while the remaining 10% were not identified. Iowa's PWSs are predominantly categorized as very small (53.9%), small (33.5%), and medium (8.1%) (Fig. 2a). Most counties feature a range of system sizes, with very small and small systems prevailing (Fig. 2b). Only 4% of Iowa's PWSs have nitrate treatment facilities; small systems face unique challenges related to funding, maintenance, public health, environmental protection, and compliance with water quality standards.[40]

Average nitrate concentrations in Iowa's PWSs

Approximately 73% of the PWSs have a 10-year average nitrate concentration less than 1 mg L^{-1} (Fig. 3a), the minimal risk level outlined in environmental health guidelines.[56] This observation translates to approximately 1.3 million Iowans receiving treated drinking water with low nitrate concentration (Fig. 3b), despite the absence of nitrate removal processes in their systems. This may be attributed to sourcing water from deeper aquifers that are less affected by nitrate contamination.[57–59]

The second most common range for nitrate concentrations is between 1 and 3 mg L^{-1}, covering about 15% of Iowa's PWSs and serving approximately 578 687 people. These concentrations, though not immediately hazardous, warrant monitoring to prevent any potential escalation that could affect public health. Around 11.6% of the public water systems, serving 763 992 people, have average concentrations above 3 mg L^{-1}. Consistent exposure to these nitrate levels, particularly for vulnerable populations,

may pose significant health risks. A study in Iowa found that long-term exposure (over five years) to average nitrate concentrations above 2.98 mg L^{-1} in public water systems was associated with increased incidences of ovarian, bladder, and breast cancer in postmenopausal women.[12,13,15] This subset of the data underscores the need for targeted water quality interventions and continuous monitoring to ensure public safety.

We performed statistical analysis for the nitrate levels for all facilities and determined that applying an average value is an appropriate approach for comparison (see ESI† – statistical analysis of nitrate concentration data). Average nitrate concentrations in Iowa's PWSs increased between 2012 and 2016, followed by a decline until 2020, and a resurgence through 2022 (Fig. 4). The decline and resurgence trends are significant at $p < 0.05$. A drought in 2012 that led to the accumulation of substantial nitrogen (N) in soils was followed by record spring rainfall in 2013. The transition from a dry to a wet year created conditions facilitating nitrogen transport from agricultural areas to water bodies, which resulted in a more than 400% increase in the amount of nitrate detected in Iowa streams from 2012 to 2013.[21] This surge made 2013 one of the worst years in recent decades for nitrate pollution, with the absolute amount of nitrate in streams statewide trending upward until 2016,[60–62] This also led to elevated nitrate levels in treated drinking water as observed in Fig. 4, despite the existence of nitrate removal measures at the treatment plants.[62]

Average nitrate concentrations in PWSs without nitrate treatment are lower than in all PWSs (Fig. 4). While this may appear counterintuitive, it is not surprising. PWSs with nitrate removal facilities have higher nitrate concentrations in their raw water sources. Even after treatment, nitrate levels are only reduced to just below the MCL to comply with regulations. This treated water often still has higher nitrate concentrations than the raw water in many PWSs without nitrate removal facilities. The effectiveness of the existing treatment systems varies, with some possibly being outdated or not sufficiently robust to handle the increasing nitrate levels.[63–65] Furthermore, the time it takes for facilities to adapt or upgrade their treatment processes can result in ongoing exposure to higher nitrates.[66] These nuances are important in understanding the data and the complex interplay of environmental factors, infrastructure capabilities, and the efficacy of current water treatment methods.

Hotspots

PWSs located in regions 3, 4, 5, and 6, corresponding to the Eastern and Western parts of Iowa, tend to have higher nitrate concentrations (Fig. 5). Eastern Iowa has 16 hotspots, or PWSs with an average nitrate concentration exceeding 5 mg L^{-1}, whereas Western Iowa has 18. Despite having fewer hotspots, the average nitrate concentration in Eastern Iowa (6.74 mg L^{-1} with a standard deviation of 2.29) is higher than in Western Iowa (6.36 mg L^{-1} with a standard deviation of
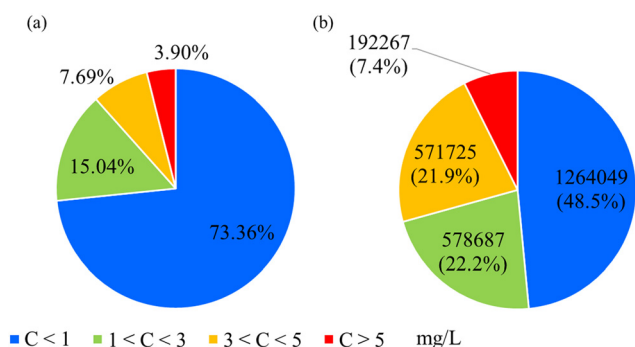

Fig. 3 Average nitrate concentrations and population exposed: (a) average nitrate concentration for 871 PWSs. (b) Fraction of population exposed to different nitrate concentrations across Iowa.
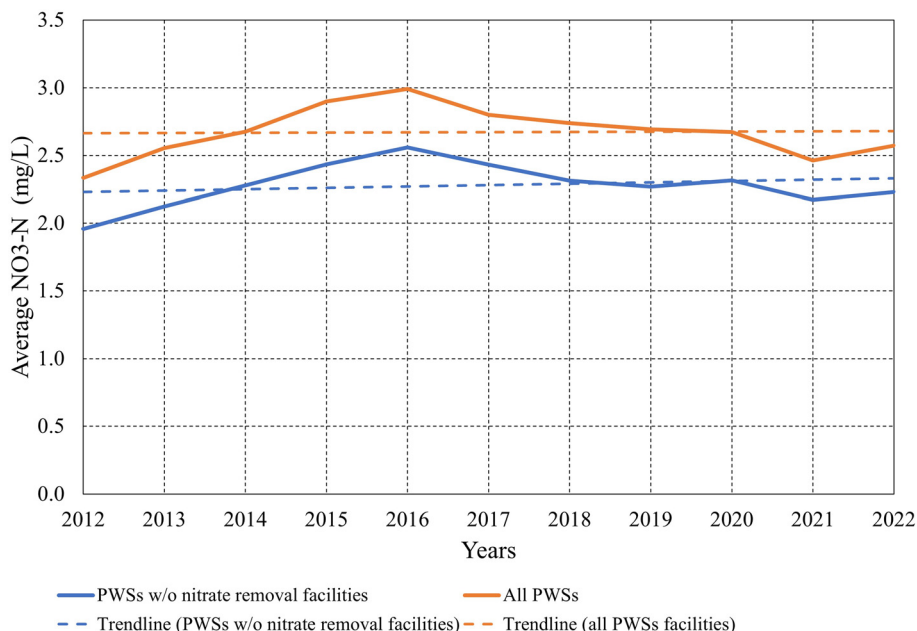
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Environ. Sci.: Water Res. Technol., 2025, 11, 959–971 | 963

Fig. 4 Average nitrate concentration across Iowa PWSs between 2012 and 2022. Thick blue line is averaged for PWSs without nitrate removal facilities. Thick orange line is averaged for all PWSs. Dashed lines are trendlines for both cases.

1.65), of which both are statistically significant at $p < 0.05$. Previous studies have shown that nitrate contamination in groundwater is particularly severe in these regions: Eastern Iowa (Floyd, Bremer, Tama, Jasper counties) with contamination in 11% of the wells, Western Iowa (Sioux, Cherokee, Ida, Cass counties) with contamination in 38.2% of the wells, and South-Central Iowa (Polk, Clarke, Wayne counties) with contamination in 28.1% of the wells.[67,68] High nitrate concentrations in certain regions may be linked to the limited adoption of advanced treatment technologies[69] as well as local agricultural activities and geological conditions affecting water quality.[60,69] In our preliminary observation, the spatial pattern of these hotspots somewhat aligns with the distribution of confined animal operations in Iowa.[70] However, it is outside the scope of this study to analyze the relationship between the spatial patterns of nitrate hotspots and the distribution of confined animal operations.

Temporal trends in Iowa PWSs

There are 19 high-risk PWSs—or facilities with average nitrate concentrations consistently above 5 mg L^{-1}—and 750 low-risk PWSs (Fig. 6 and S4†). Average nitrate concentrations increased over the study period for 512 PWSs, with high-risk facilities showing levels ranging from 4 to 9 mg L^{-1}. Conversely, 311 PWSs exhibited a decreasing trend in nitrate levels, while 11 PWSs maintained consistently low nitrate concentrations, averaging around 0.05 mg L^{-1} over the study period. In Eastern Iowa (regions 5 and 6), ten PWSs were classified as high-risk, while in Western Iowa (regions 3 and 4), nine PWSs were high-risk. Seven of the nine high-risk PWSs in Western Iowa showed an upward trend in nitrate

levels, whereas in Eastern Iowa, five out of ten high-risk PWSs displayed a similar upward trend. Overall, there are 12 PWSs classified as high-risk with an upward trend, and 7 high-risk PWSs that show a downward trend. There are 470 PWSs classified as low-risk but with an upward trend. The high-risk PWSs with an upward trend are particularly concerning due to their consistently high nitrate concentrations and lack of signs of improvement. Amongst these systems, ten are identified as small systems and only two are large systems. Only one of the 12 PWSs had implemented a nitrate treatment method. This observation highlights the vulnerability of small systems and the reliance of these systems on source water quality rather than active mitigation strategies.

Disparities in potential nitrate exposure

There are noticeable disparities among different sociodemographic groups regarding potential exposure to average nitrate concentrations exceeding 5 mg L^{-1} in their drinking water across all active PWSs with no inclusion of private wells. On average, 7.4% of Iowa's population has been exposed to nitrate concentrations exceeding 5 mg L^{-1} in the past decade. Certain groups face higher exposure rates: 9.2% of people of colour, 10.1% of low-income individuals, 9.6% of adults aged 65 and older, and 8.7% of children aged 5 and under. The unequal variances t-test suggests that results are significant at $p < 0.05$. We further analysed disparities by dividing the data into two distinct periods: 2012–2016 and 2017–2022, given that annual average nitrate concentrations peaked in 2016 (Fig. 4). Despite a decline in average nitrate concentrations after 2016, significant disparities among
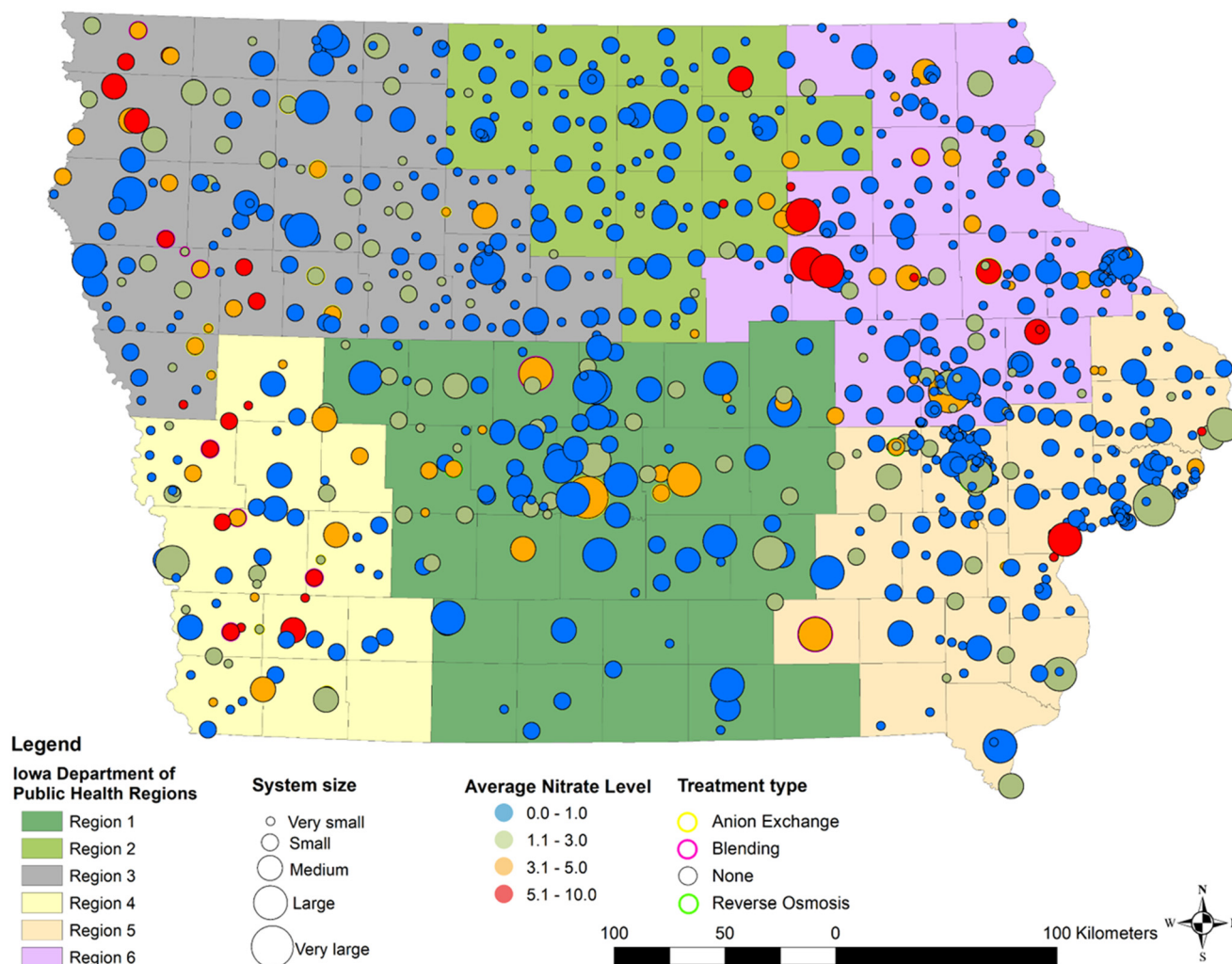
964 | *Environ. Sci.: Water Res. Technol.*, 2025, **11**, 959–971

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Fig. 5 Nitrate concentration averaged for 2012–2022 for each PWS in Iowa. Outline color indicates the type of nitrate removal process. Size of circle indicates system size. Underlying background color indicates Iowa Department of Public Health Regional Medical Coordination Centres.

sociodemographic groups remain statistically significant (Table S1†).

We also analysed disparities at the county level by aggregating the results of individual PWS to the counties where they are located (Fig. 7). County names and population density are detailed in Fig. S5.† The *x*-axis represents nitrate concentration averaged at the county level for all PWSs with concentrations ranging from 0.1 mg L^{-1} to 5.1 mg L^{-1} which is consistent throughout Fig. 7; the *y*-axis are different for each category: people of colour - 0 to 47%, low-income individuals - 2% to 49%, adults aged 65 and older - 2% to 27%, and children aged 5 and younger - 1% to 8%. Counties such as Black Hawk, Wapello, and Crawford, where percentages of people of colour are relatively high, all have average nitrate concentrations exceeding 5 mg L^{-1} (Fig. 7a). For low-income individuals, we observed that counties such as Black Hawk, Crawford, Audubon, Cass, and Jasper exhibit both a high percentage of low-income individuals and high average nitrate concentrations in drinking water (Fig. 7b). For adults aged 65 and older, we identified disparities in counties

such as Butler, Monona, Audubon, and Cass (Fig. 7c). For children aged 5 and younger, counties such as Black Hawk, Crawford, Butler, Cass, and Boone exhibit concerning high nitrate concentrations, putting young children at risk (Fig. 7d). Black Hawk and Crawford counties appear in all categories except for adults aged 65 and older, highlighting discernible disparities in nitrate exposure among different sociodemographic groups in these regions. Black Hawk County has nine PWSs, seven of which are categorized as small systems. In Crawford County, all public water systems are small. Despite the high nitrate concentrations in their drinking water, none of the PWSs in these two counties have implemented nitrate removal processes. The average nitrate concentrations in the finished water supplied to homes were as high as 7.2 mg L^{-1} in Black Hawk County and 8.1 mg L^{-1} in Crawford County. Nitrogen fertilizer application in Black Hawk County contributes to the high nitrate in its groundwater wells, which are the main source of drinking water for the county.[71] As the fifth most populous county in Iowa, Black Hawk faces the challenge of balancing economic

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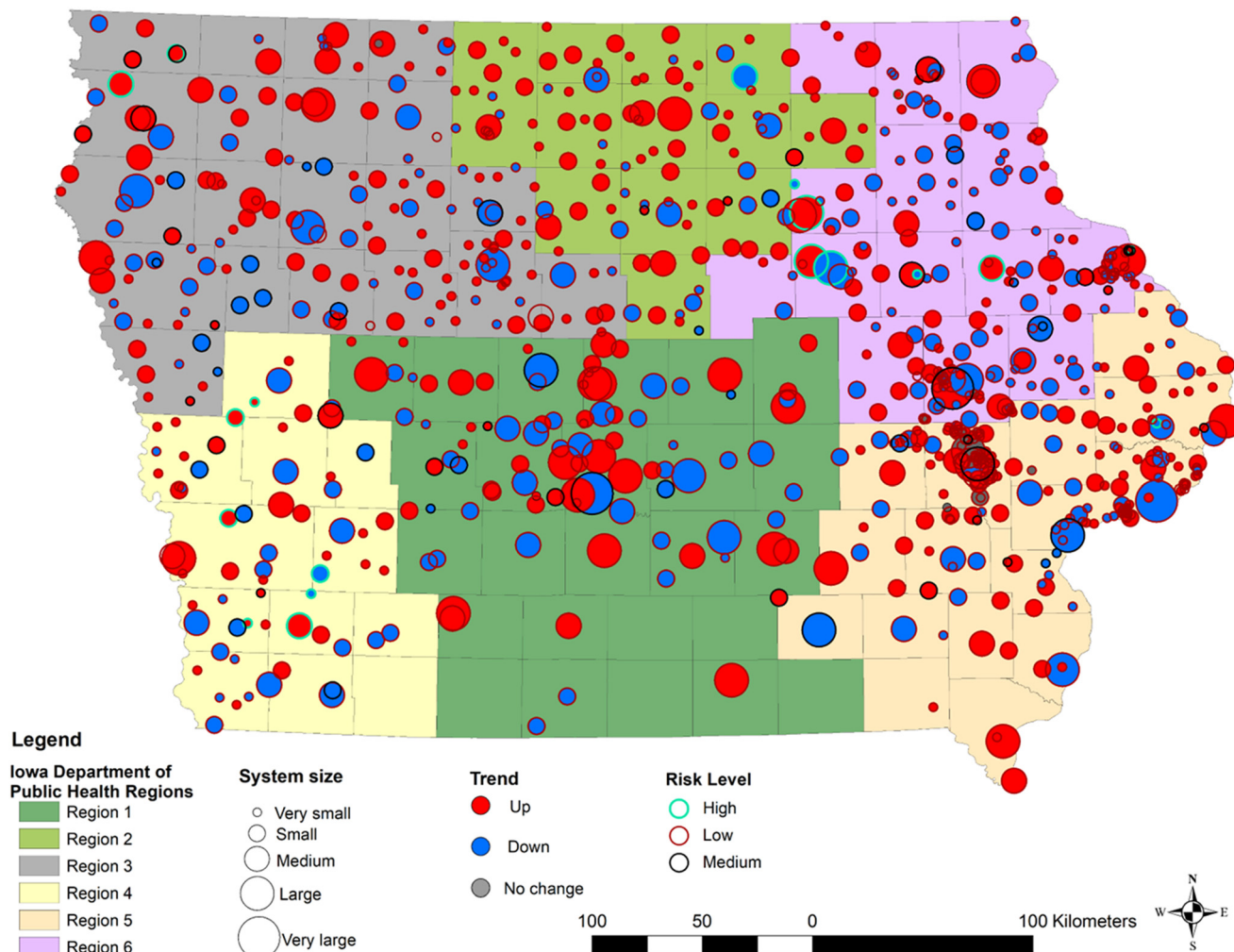*Environ. Sci.: Water Res. Technol.*, 2025, **11**, 959–971 | **965**

Fig. 6 Trend of average nitrate concentration between 2012 and 2022 for each PWS in Iowa. Outline color indicates risk level. Size of circle indicates system size. Underlying background color indicates Iowa Department of Public Health regions.

growth with the imperative of ensuring safe and clean drinking water for its residents, particularly for the most vulnerable sociodemographic groups. According to the U.S. Centers for Disease Control and Prevention, Crawford County has the highest social vulnerability index score in the region.[72] It also ranks among the twelve Iowa counties most at risk for drought.[73] These factors exacerbate concerns for Crawford County communities, which are already struggling with limited resources to address nitrate contamination in their drinking water while grappling with ongoing water scarcity issues.[57–60]

Adequately treating nitrate in drinking water requires substantial investment. The current EPA MCL of 10 mg L^{-1} was set to balance financial feasibility with public health protection.[74] Recent epidemiological studies have shown that ingesting nitrate at lower than MCL levels for an extended period still results in severe adverse health outcomes,[12,13,15] leading to significant economic costs. One study estimates a potential economic impact of $1.3 to $6.5 billion in lost productivity across the United States, using a high nitrate

threshold of 4.5 mg L^{-1}.[5] Another study demonstrated that reducing nitrate concentration from 10 mg L^{-1} to 3.87 mg L^{-1} could yield about $302 million dollars economic health benefits in Denmark.[75] These findings highlight that the economic benefits of lowering nitrate levels can outweigh the associated costs, providing a strong case for revising current nitrate standards. While our study does not challenge the importance of the current MCL, we emphasize the need to investigate the adverse health risks associated with nitrate levels below the MCL, particularly their disproportionate impact on marginalized communities with limited resources.

All in all, our results underscore the necessity for public health policies and environmental regulations that specifically address the needs of the most vulnerable populations.

Conclusion

Iowa is dominated by small and very small PWSs, according to EPA categorization. Addressing nitrate contamination in
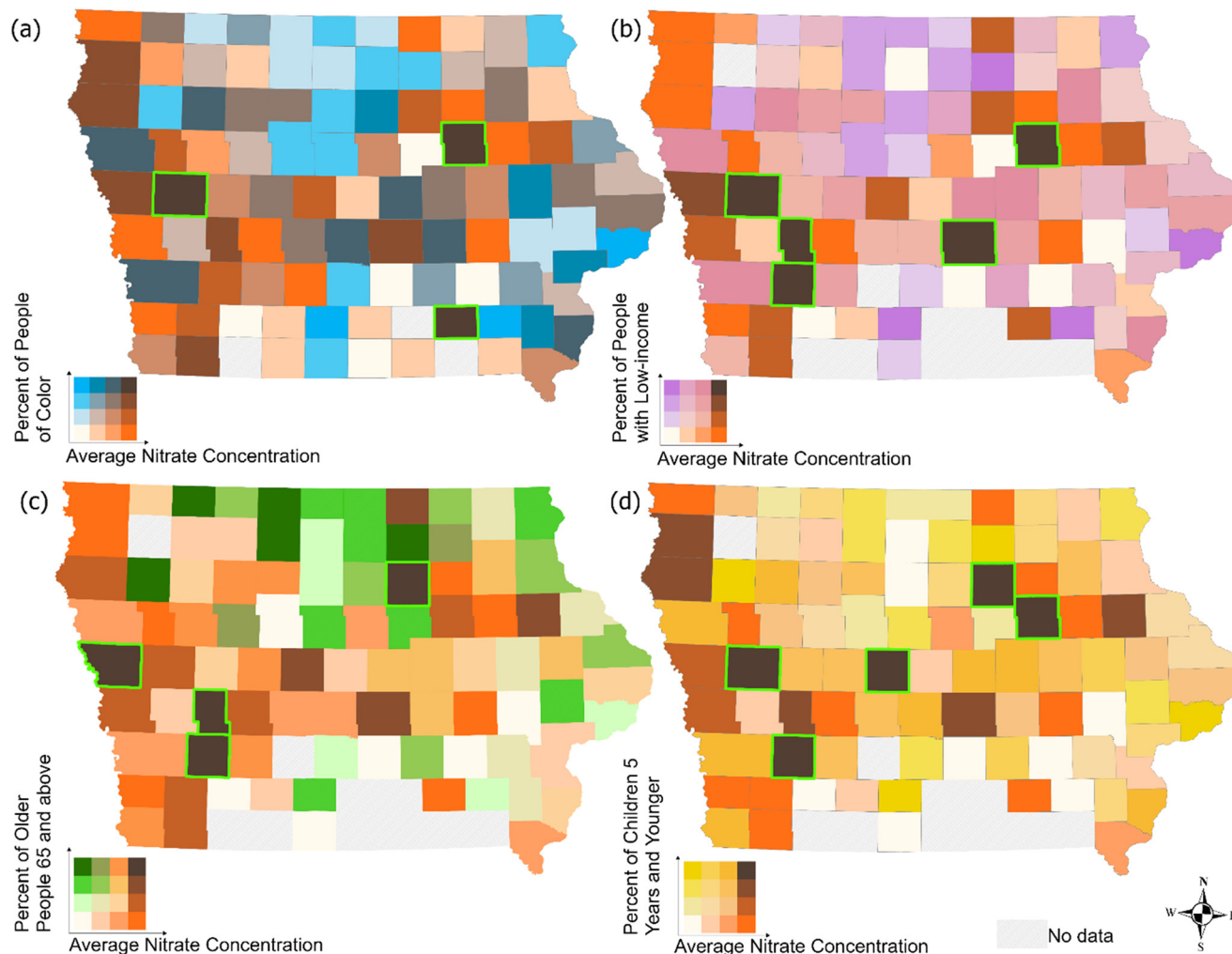
Fig. 7 Disparity in potential nitrate exposure among different sociodemographic groups (a) people of colour (b) low-income communities (c) older people 65 and above and (d) children 5 years and younger. The hatchet areas depict areas that do not have or report any information in EPA ECHO. Counties named in the text are highlighted with green outlines.

the state's drinking water has long been a challenge, particularly for small and under-resourced communities, which make up the majority in Iowa. Our study tracks the long-term trends of nitrate concentrations across 871 active PWSs in Iowa and identifies critical 'hotspots' requiring immediate intervention. Notably, Eastern and Western Iowa (Regions 3, 4, 5, and 6) are areas of high concern, with average nitrate levels consistently exceeding 5 mg L^{-1} throughout the study period for many PWSs in these two regions. The absence of advanced nitrate removal technologies, such as anion exchange and reverse osmosis, exacerbates the problem, contributing to persistently high nitrate levels in these communities' drinking water.

Furthermore, our analysis reveals that low-income individuals, older adults, children, and people of colour are disproportionately affected by high nitrate levels, with these groups experiencing higher rates of exposure compared to the state average of 7.4%. We have identified 'hotspot' counties where PWSs exhibit elevated nitrate concentrations,

frequently in socially vulnerable communities. These findings underscore the need for targeted interventions to lower nitrate levels in water supplies, especially in high-risk areas, to safeguard the health of Iowa's most vulnerable populations. The implications of these findings extend beyond immediate health concerns, emphasizing a need for infrastructure investment in water treatment facilities, especially in the high-risk areas we've identified. This issue intersects with public health and social equity, as the situation at hand disproportionately affects disadvantaged communities. On a policy level, there may be a need to revise regulatory standards and enforcement to ensure safer water for Iowans and the nation as a whole since epidemiological studies show that even lower levels could potentially harm human health. Moreover, our findings advocate for initiating more robust public health initiatives, which could include enhanced water quality monitoring to ensure the risks are managed proactively. Public awareness campaigns and community support programs are also essential in mitigating

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Environ. Sci.: Water Res. Technol., 2025, **11**, 959–971 | **967**

the risks associated with nitrate exposure until more permanent solutions take hold. By addressing these issues comprehensively, there is an opportunity to improve health outcomes and advance environmental justice, ensuring that all residents have access to safe drinking water.

Data availability

The datasets generated and analyzed during this study are available from the corresponding author upon request.

Author contributions

E. P. M. was responsible for data curation, formal analysis, and investigation; he developed the methodology, contributed software and resources, created visualizations, and wrote the original draft. L. L. conceptualized the project, secured the necessary funding, and oversaw project administration, providing essential resources and supervision; she also contributed to validating the work and reviewing and editing the paper. C. R. contributed to acquiring funding, managing the project, providing necessary resources, assisting in the validation process, and reviewing and editing the paper.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

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