

Hydrogeochemical Suitability of Groundwater for Irrigation and Agriculture: A Sodium Adsorption Ratio, Kelley Index and Irrigation Water Quality Index Analysis of Sedimentary and Basement Aquifers in Southwestern Nigeria

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ABSTRACT

Agricultural water resource management in sub-Saharan Africa increasingly relies on groundwater resources that have seldom been hydrogeochemically characterized for their suitability in irrigation water supply. In Sobe community in Edo State and Elegbeka community in Ondo State, southwestern Nigeria, groundwater from hand-dug well water supplies both domestic and agricultural water uses. However, their suitability for irrigation water supply has never been evaluated with hydrogeochemical indices of irrigation water quality. This study evaluated the Sodium Adsorption Ratio (SAR), Kelley Index (KI), Permeability Index (PI), Magnesium Hazard (MH), and a composite Irrigation Water Quality Index (IWQI) on groundwater from 25 sampling points across two geological terrains: Imo shale geological series and Basement Complex migmatite. The results showed that although concentrations of potassium ion are 10 to 18 times higher than permissible limits for domestic water supply by NAFDAC, they are a major agronomic benefit to low-fertility soils. This poses a domestic/agricultural water trade-off with policy implications. Although SAR values classify all groundwater from these two study areas as low to medium salinity hazard, chloride and sulphate ion concentrations in some of the water samples from Elegbeka community result in a high salinity hazard classification for water from Wells 6 and 10. Magnesium ion concentrations greater than 50% classify water from these two wells in Elegbeka community as unfit for irrigation water supply. From the Kelley Index calculation results, 79% of Sobe community water wells are suitable for irrigation water supply compared to 60% of water wells in Elegbeka community. The hardness-dominated water chemistry of water from Elegbeka community poses a precipitation hazard to soil permeability in fine-textured soil plots. This study provides a first-time characterization of water suitability for these two communities and can be a model for promoting safe water use for agriculture and protecting food security.

Keywords: irrigation water quality; sodium adsorption ratio; Kelley index; magnesium hazard; Hydrogeochemistry; Nigeria; food security; groundwater agriculture

INTRODUCTION

Food security in the rural regions of sub-Saharan Africa is inextricably linked to the availability and quality of agricultural water. Smallholder farming, which accounts for 70% of food production in Nigeria, is largely reliant on groundwater as a source of water for dry-season irrigation, particularly in regions where surface water is seasonal or contaminated (FAO, 2021; Olabisi & Ramaswami, 2022). The evaluation of groundwater quality for agricultural use, however, has garnered relatively less analytical attention compared to domestic use, thereby leading to a significant knowledge gap with respect to the water-food-environment interface for the rural Nigerian population (Kawo & Karuppanan, 2018; Adimalla et al., 2020).

The quality of water for agricultural use is defined by a unique set of physical and chemical parameters, which differ significantly from those applied for evaluating water quality for domestic use. The quality of irrigation

water is largely focused on the salinisation potential of water, which is defined by the total dissolved solids content and the electrical conductivity, sodification, which is defined by the sodium adsorption ratio and Kelley index, permeability, which is defined by the permeability index and magnesium hazard, and the ion-specific toxicity, particularly for sodium, chloride, and boron, which can be detrimental to certain crop plants. Domestic water quality standards, as defined by NAFDAC and WHO, do not account for the unique parameters applicable to irrigation water, and the concentration ranges for irrigation water, which might be suitable, unsuitable, or detrimental, can differ significantly from those applicable for domestic use.

A good example of the domestic-agricultural trade-off is the potassium (K) results obtained from the two study areas, Sobe and Elegbeka, where potassium levels are higher than the domestic regulatory limit of 10 mg/L by a factor of 8-18 (ranging from 75 to 196 mg/L). While the elevated potassium levels are a regulatory concern in the context of domestic water quality, it is a macronutrient required by plants in order for them to carry out metabolic processes, and its application as part of the irrigation water constitutes a net agronomic benefit, especially in the lateritic leached soils of south-western Nigeria, where potassium deficiency is cited as one of the constraints to crop yield (Adeyemo & Agele, 2010). This domestic-agricultural trade-off has not previously been reported in any of the study areas and constitutes a novel contribution of the research results.

In the case of the elevated total hardness of the groundwater of the Elegbeka community, while it is a regulatory concern in the context of domestic water quality, it is beneficial in the context of irrigation water as it supplies calcium and magnesium to the soils. While the elevated total hardness of the groundwater of the Elegbeka community is beneficial in the context of irrigation water as it supplies calcium and magnesium to the soils, the dominance of magnesium over calcium in the mineral composition of the waters of some of the wells in the Elegbeka community, especially Wells 6 and 10 where $MgCO_3$ approaches or equals $CaCO_3$, constitutes a Magnesium Hazard that would negatively affect soil structure if the waters are used in irrigation.

This study aims to bridge the identified research gap by using the full range of established indices for evaluating the water quality of irrigation water: SAR, KI, PI, MH, and IWQI. The overarching research question is: What is the irrigation water quality of the groundwater from the Imo Shale Formation Sobe and Basement Complex Elegbeka aquifers, and how does it vary seasonally and spatially?

Theoretical Framework

This Study is Predicated on the Integrated Hydrogeochemistry-Agronomy Framework (IHAF) that Conceives the Quality of Irrigation Water as a Function of the Interaction of the Hydrogeochemical System, which Regulates the Ion Composition in Water; the Soil-Water Interface System, which Regulates Ion Exchange, Salinization, and Permeability; and the Crop Physiology System, which Regulates Ion Tolerance. IHAF, as Conceived by Kawo and Karuppannan (2018) and Adimalla et al. (2020), Provides a More Holistic Perspective than Hydrochemistry or Agronomy Alone because it Allows for the Identification of Complex Interactions, Like the Antagonism between Calcium and Magnesium in Soil Permeability.

This Study Complements the IHAF Perspective by Using the Theory of Integrated Natural Resource Management (INRM) as Conceived by Sanginga and Woomer (2009), which Holds that the Soil, Water, and Crop Resource Systems Must be Managed as a Single Entity Rather than as Individual Resources. In the INRM Perspective, the Groundwater Resource of Sobe and Elegbeka is Not Just a Source of Potable Water or a Receptacle for Pollutants; it is a Resource for Crop Production whose Quality Characteristics Interact with the Crop's Requirements and the Soil's Chemistry to Produce the Desired Crop Yield and Long-Term Sustainability.

MATERIALS AND METHODS

Study Area

Full descriptions of the study areas (Sobe, Owan West LGA, Edo State; and Elegbeka, Ose LGA, Ondo State) are provided in the companion publication (Osayande & Umukoro, 2025). The samples were collected randomly but strategically to cover the entire study area ensuring a fair distribution. Briefly, Sobe overlies Imo Shale sedimentary formation (southern Anambra Basin), while Elegbeka is underlain by migmatite basement complex

rocks with an abundant dumpsite presence and shallow water table (3–6.7 m depth). The climate is tropical subequatorial, with a wet season (April–October) and a dry season (November–March). Agricultural activities in both communities include subsistence food crop cultivation (cassava, yam, vegetable gardens), for which groundwater is used during the dry season.

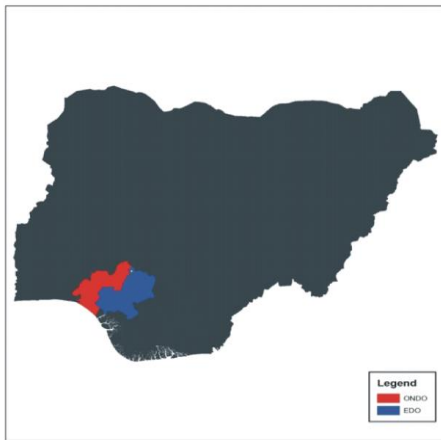


Figure 1 Map of Nigeria showing Edo and Ondo States



Figure 2 Map of Ondo and Edo State showing the studied area.

Sample Collection

Fifteen (15) water samples were collected from twelve (12) hand dug wells, one (1) borehole and two (2) rivers during the dry season in the month of February 2011 in Sobe community of Edo State. Subsequently in the month of September 2011 the same wells earlier sampled in February were sampled again to observe if there would be any seasonal variations in the quality and quantity of the water. Ten (10) water samples were taken similarly from Hand dug wells in Elegbeka Community in Ose local Government Area, Ondo State which lies on the southwestern axis of the Nigerian Basement Complex. Bringing the total number of samples analyzed to twenty-five (25). The samples were collected randomly but strategically to cover the entire study area ensuring a fair distribution. The choice of wells depends on distance from previously chosen wells in the locality and more importantly the consent of the owner to make is well available for study. Samples were drawn with the aid of locally made plastic drawer into two different types of polyethylene bottles i.e 1.5L for physico-chemical parameter and 0.75L plastic bottle also for physico-chemical and microbial analyses. Samples were immediately transported to Laboratory and kept @4oC prior the time of the analyses.

Physicochemical Analysis

The pH and electrical conductivity of the samples was determined using a digital Ph meter model GMBH D4040 NEUSSI and a conductivity meter; Radiometer and Copen-Hagen CDM83. The Turbidity of the samples was ascertained at a specified wavelength using a HACK DR 2010 datalogging spectrophotometer. The total dissolved solids of the samples were determined using gravimetric procedure as described by Ademoroti, (1996). The total hardness, total alkalinity and sulphate content of the samples were evaluated using titrimetric and turbidimetric method as stated by Ademoroti, (1996).

The chloride and nitrate values of the samples were determined using Mohr's Method APHA 1993 and colorimetric method APHA, 1993 respectively. The phosphate content of the samples was evaluated using the ascorbic acid reduction described by ASTM, 1990. The heavy metals; Cu, Cr, Ni, Pb, Cd, Zn, Fe and Mn concentrations of the water samples were determined with the aid of an atomic absorbance spectrophotometer AAS;BUCK SCIENTIFIC Model 210 VGP USA..

Bacteriological Analysis

The total coliform and fecal coliform (*Escherichia coli*) counts of the samples were evaluated using the multiple tube technique as described by APHA, (1993); Cheesebrough, (2000) and Aneja, (2003). The resulting coliform cultures were characterized and identified keys stated by Holt, (1989); Farmer, (1995) and Gullimore, (2000).

Data Source and Variables Selected

The irrigation suitability analysis utilises the following parameters from the original physicochemical dataset: Electrical Conductivity (EC, $\mu\text{S}/\text{cm}$), Total Dissolved Solids (TDS, mg/L), Sodium (Na^+ , mg/L), Calcium (Ca^{2+} , mg/L), Magnesium (Mg^{2+} , mg/L), Chloride (Cl^- , mg/L), Sulphate (SO_4^{2-} , mg/L), Bicarbonate (HCO_3^- , mg/L), Potassium (K^+ , mg/L), and Total Hardness ($\text{mg}/\text{L CaCO}_3$). Heavy metal data are drawn upon selectively where ions of agronomic significance are relevant. These variables were measured across 25 sampling points (15 Sobe, 10 Elegbeka) in two seasons (dry season: February 2011; wet season: September 2011).

Irrigation Water Quality Indices

The following indices were calculated using standard formulae, with ionic concentrations converted to milliequivalents per litre (meq/L) as required:

Sodium Adsorption Ratio (SAR) = $\text{Na} / \sqrt{[(\text{Ca} + \text{Mg})/2]}$, where SAR < 10 = excellent; 10–18 = good; 18–26 = doubtful; >26 = unsuitable (Richards, 1954).

Kelley Index (KI) = $\text{Na} / (\text{Ca} + \text{Mg})$, where KI < 1 = suitable; KI > 1 = unsuitable for irrigation (Kelley, 1963).

Permeability Index (PI) = $[\text{Na} + \sqrt{\text{HCO}_3}] / [\text{Ca} + \text{Mg} + \text{Na}] \times 100$. Class I (PI > 75%): excellent; Class II (PI 25–75%): good; Class III (PI < 25%): unsuitable (Doneen, 1964).

Magnesium Hazard (MH) = $\text{Mg} / (\text{Ca} + \text{Mg}) \times 100$. MH > 50% = high magnesium hazard, unsuitable for irrigation.

EC was classified using the USDA salinity classification: C1 (<250 $\mu\text{S}/\text{cm}$): low; C2 (250–750 $\mu\text{S}/\text{cm}$): medium; C3 (750–2250 $\mu\text{S}/\text{cm}$): high; C4 (>2250 $\mu\text{S}/\text{cm}$): very high salinity hazard.

A composite Irrigation Water Quality Index (IWQI) was constructed following Meireles et al. (2010), using a weighted method of normalisation of EC, SAR, Na, Cl, and HCO_3 . The weights used correspond to the relative importance of each parameter in soil-crop interaction. IWQI classification: 85-100 (no restriction); 70-85 (low restriction); 55-70 (moderate restriction); 40-55 (high restriction); below 40 (very high restriction).

RESULTS

Salinity Hazard (EC and TDS Classification)

The electrical conductivity of the wells in the Sobe area during the dry season varied from 10 to 350 $\mu\text{S}/\text{cm}$, with a median of 60 $\mu\text{S}/\text{cm}$. Most of the wells fall in the C1 class of low salinity hazard. However, the electrical conductivity of the wells during the wet season varied from 40 to 1,670 $\mu\text{S}/\text{cm}$. Wells 8 and 9 recorded 800 and 1,670 $\mu\text{S}/\text{cm}$, reclassifying them from C1 to C3 (high salinity hazard). This anomaly of higher salinity in the wet season than in the dry season is a result of the higher TDS observed in the wet season in the two wells. In the wet season, the TDS was 536 and 1,118 mg/L for Wells 8 and 9, respectively. This is a result of the leaching of soluble salts from the soil surface into the aquifer.

In the case of EC in Elegbeka, there is an opposite trend for most wells, with values in the range of 40 to 870 $\mu\text{S}/\text{cm}$ during the dry season and 130 to 2,020 $\mu\text{S}/\text{cm}$ during the wet season. For Wells 6, 7, and 10 in Elegbeka, which fall in the C3-C4 classification, the spike in the wet season is attributed to the infiltration of leachate from the proximate dumpsites. Water from these three wells is not suitable for irrigation of salt-sensitive crops such as tomatoes and leafy greens and is a high salinity hazard for irrigation of other crops.

Sodium Hazard (SAR and Kelley Index)

SAR values in Sobe range from 0.2 in the dry season for Well 13 to 3.1 in the wet season for Well 8. All Sobe wells fall in the S1 classification of excellent sodium hazard. This is in line with the low sodium concentrations observed in Sobe, with Na concentrations between 5.1 and 59.7 mg/L. The Kelley Index values range from 0.08 to 0.72, with all values being below 1.0, which is the critical value for irrigation suitability.

In the case of Elegbeka, the situation is more complex. During the dry season, the values range from 0.21 in Well 3 to 3.8 in Well 6. All the values fall in the excellent classification. During the wet season, the unusually high Na concentrations in Wells 6 and 10, which contain leachate from dumpsites, result in an increase in the SAR values to 4.7 and 5.8, respectively, which is close to the S2 classification for medium sodium hazard.

The Kelley Index for the wet season in Well 10 is 0.92, which is close to the critical value of 1.0.

Permeability Index

The Permeability Index of the Sobe dry season wells ranged from 41% to 78%, with the majority classified as Class II (good permeability), with Wells 3, 7, and 13 classified as Class I ($\text{PI} > 75\%$). In the wet season, the PI slightly decreased, ranging from 38% to 72%, due to the reduction in the concentration of the bicarbonate ion. In Elegbeka, the Permeability Index of the dry season wells ranged from 36% (Well 6) to 79% (Well 3), with only Well 6 classified as Class II (marginal), while the rest were classified as Class II-I. High levels of bicarbonate in Elegbeka Wells 6 (272 mg/L dry) and Well 10 (170 mg/L dry) lower the PI value. However, the high levels of calcium-dominated hardness tend to offset the reduction in permeability caused by the high levels of sodium.

Magnesium Hazard

The analysis of the Magnesium Hazard shows the highest level of agricultural risk differentiation between the two terrains. In the Sobe wells, the MH ranged from 24% (Well 9) to 67% (Well 2) in the dry season, with 6 of the 13 wells exceeding 50%. In the Elegbeka wells, the MH range was much higher, ranging from 21% (Well 8) to 89% (Well 6) in the dry season. In Elegbeka Well 6, the MgCO_3 hardness level of 416 mg/L is much higher than the CaCO_3 hardness level of 258 mg/L, resulting in a MH of 61%. At this level, irrigation would eventually replace the calcium in the soil exchange complex, leading to soil structure degradation.

The geological basis for this is obvious: the basement complex migmatites and biotite gneisses of Elegbeka contain more magnesium than calcium compared to the calcareous composition of the Imo Shale of Sobe. The generally higher values of MH in Elegbeka than Sobe (mean values: 54% and 43%, respectively) also support

this lithology-based control on IWQI values, making the geology a first-order determinant of irrigation suitability even before the effects of anthropogenic contamination.

Composite IWQI Classification

The composite IWQI values show a complex pattern. For Sobe, IWQI values for the dry season ranged from 62 (Well 8: moderate restriction) to 91 (Well 7: no restriction). A significant proportion of Sobe wells (73%) qualified for 'low restriction' and 'no restriction' IWQI classification in the dry season. This indicates Sobe groundwater is generally a good source for irrigation purposes in the dry season. For the wet season, Sobe wells 8 and 9 qualified for 'high restriction,' indicating elevated TDS and conductivity.

In the case of Elegbeka, the IWQI values were more variable. For the dry season, IWQI values ranged from 44 (Well 6: high restriction) to 85 (Well 3: low restriction). For the wet season, wells 6, 7, and 10 qualified for 'high restriction' and 'very high restriction,' making them unsuitable for irrigation purposes.

The spatial distribution of low IWQI values for wells close to the refuse dump sites of Elegbeka supports the assertion that anthropogenic contamination is the primary determinant of irrigation unsuitability, even before the effects of geological magnesium.

The Potassium Paradox: Agricultural Asset or Domestic Liability

Potassium concentrations in all wells exceeded the NAFDAC limit of 10 mg/L for domestic use. The range of concentrations was from 75 to 195 mg/L at the Sobe dry season wells, and from 92 to 180 mg/L at the Elegbeka dry season wells.

From the perspective of domestic water quality, these concentrations represent exceedances of 7.5 to 19.5 times the permissible limit.

However, from an agronomic viewpoint, the higher potassium content is seen as a major advantage. Potassium is a major plant nutrient for plant physiology, and its role in enzyme activation, water, and photosynthate transport is critical. The soils in the study area, located in the southwestern part of Nigeria, are dominated by the Ultisols and Oxisols, which are classified as lateritic soils and tend to be potassium-deficient (Sanginga & Woomer, 2009). The application of 100 mg/L potassium at the rate of 5 mm/day would amount to the delivery of 0.5 kg/ha/day, a major agronomic value in the groundwater that is unmonetised and invisible in the water quality reports on the domestic water supplies.

DISCUSSION

Geological Terrain as a Primary Determinant of Irrigation Suitability

The major finding of the study is the determination that the geological terrain, particularly the difference between the sedimentary and basement complex terrains, is as critical a determinant of the suitability of the irrigation water as the anthropogenic contamination.

The higher MH, higher total hardness, and higher EC values in the basement complex wells in Elegbeka, for example, point to the critical role of the geological terrain, irrespective of human activities. The implication for the planning and design of irrigation water supplies in Nigeria is that the geological terrain should be factored into the planning and design of the irrigation water supplies, and index assessments conducted before recommending the use of the groundwater for agricultural purposes.

Prior studies of irrigation water quality in Nigeria have largely focused on delta and coastal aquifer systems (e.g., Nwankwoala et al., 2022; Tse et al., 2023) or on large-scale agricultural schemes in northern Nigeria (Aliyu et al., 2023). The present study contributes the first comparative basement-sedimentary irrigation suitability analysis for the southwestern transition zone, filling an important regional gap.

Seasonal Dynamics and Agricultural Calendar Implications

The seasonal reversal of irrigation suitability observed at select Sobe wells — where wet season conductivity exceeded dry season values — has practical implications for agricultural water management. Farmers who rely on these wells for dry-season vegetable cultivation face a paradox: the season in which irrigation demand is highest (dry season) is also the season when most wells have the lowest EC and thus the lowest salinity hazard. Conversely, the wells that exhibited elevated wet-season conductivity are most likely to be used in the initial period following the wet-season end, when residual moisture is insufficient and farmers begin supplemental irrigation.

Communicating this seasonal pattern to farmers through extension services is a priority recommendation of this study. Agricultural extension workers in Owan West and Ose LGAs should be equipped with simple EC meters and instructed on the USDA salinity classification system, enabling them to guide farmers in selecting appropriate wells for irrigation at different times of the agricultural calendar.

Integration with Food Safety and Crop Uptake Concerns

The irrigation suitability analysis in this study addresses water quality at the point of application. A downstream concern — the uptake of heavy metals (particularly Cr, Cd, Pb) from contaminated irrigation water into food crops — lies beyond the scope of the present analysis but warrants attention. Research from comparable settings in West Africa (Nartey et al., 2012; Abdu et al., 2021) demonstrates that prolonged irrigation with Cr- and Pb-contaminated water leads to detectable accumulation of these metals in root and leafy vegetables. Given the elevated Cr and Pb concentrations documented across Sobe and Elegbeka wells, future research should measure crop tissue metal concentrations in produce irrigated from these sources to complete the farm-to-table risk assessment for these communities.

Limitations

This study is subject to the limitation that irrigation water quality indices were designed primarily for large-scale, mechanised agriculture in arid and semi-arid regions; their sensitivity and threshold values may require calibration for smallholder subsistence farming systems in humid tropical Nigeria. Moreover, the soil physicochemical data from the study communities were not available, which would have enabled the calculation of the Leaching Requirement. Future studies should include soil texture, cation exchange capacity, and bulk density data in the irrigation suitability analysis.

Policy and Agricultural Development Implications

- State agricultural development agencies in Edo and Ondo States should prioritize the testing of irrigation water sources in communities with identified refuse dump sites, using SAR, KI, and IWQI as the major criteria
- The finding of elevated potassium in groundwater should be incorporated into fertiliser recommendation protocols for smallholder farmers in Sobe and Elegbeka, potentially reducing the required potassium fertiliser application rate and farm input costs.
- Wells with MH > 50% in Elegbeka (particularly Wells 6 and 10) should not be recommended as primary irrigation sources without gypsum amendment (to replace magnesium with calcium in irrigated soils) or blending with lower-MH water sources.
- Seasonal EC monitoring should be established for wells used in dry-season irrigation in both communities, with farmer training on interpreting EC readings.
- Refuse dump relocation remains a priority not only for domestic water quality (as recommended by Osayande & Umukoro, 2025) but also for agricultural water quality, given the dumpsite-driven deterioration of IWQI scores in Elegbeka's wet season.

Sustainable Development Goal Alignment

This study contributes directly to SDG 2 (Zero Hunger) by providing the evidence base for optimising agricultural water use in food-insecure rural communities. The identification of high-potassium groundwater as an agronomic asset supports SDG 2.3 (smallholder productivity enhancement). SDG 6 (Clean Water and Sanitation) and SDG 6.4 (irrigation efficiency and sustainable water withdrawals) are both served by the irrigation suitability analysis. SDG 15 (Life on Land) is addressed through the soil protection implications of the magnesium hazard and salinity risk findings. The study's equitable treatment of two communities with different geological endowments and risk profiles contributes to SDG 10 (Reduced Inequalities).

CONCLUSION

This study presents the first systematic hydrogeochemical irrigation suitability assessment for groundwater in the Sobe (Imo Shale) and Elegbeka (Basement Complex) communities of southwestern Nigeria. Applying the SAR, Kelley Index, Permeability Index, Magnesium Hazard, and composite IWQI to a 25-sample, dual-season, dual-geology dataset, the study demonstrates that the majority of Sobe wells qualify for low-restriction irrigation use in the dry season, while Elegbeka wells exhibit greater heterogeneity, with three wells (6, 7, 10) falling into the high- or very high-restriction categories during the wet season due to elevated conductivity, sodium, and dumpsite-derived contamination. The geological control of the hazard, which was higher in the basement complex Elegbeka than the sedimentary Sobe, is a new and relevant discovery. The paradox of potassium, which was a regulatory exceedance from a domestic standard but a positive agronomic response, questions the validity of domestic water standards as the only basis for water quality assessment. The findings suggest a need to consider irrigation suitability indices as part of the Nigerian rural water quality governance process, as well as the development of advisory services for smallholder farmers.

Author Contributions

A.I.U.; Conceptualization, data collection, laboratory analysis, writing—original draft. A.D.O.; Methodology review, writing—review and editing.

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Competing Interests

The authors declare no competing interests in relation to this manuscript.

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