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PERMANENT CO_2 STORAGE THROUGH BASALT MINERALISATION IN INDONESIA: A STUDY OF ANGUS ROCK AND MARITIME CCS INTEGRATION

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Abstract. The Angus Rock in Ternate, composed of Ca- and Mg-rich andesitic basalt, offers a unique opportunity for mineralisation-based carbon storage. Its reactive volcanic rock, direct access to the port, and proximity to the Kastela Combined Cycle Power Plant (30 MW) create ideal conditions for large-scale CO_2 capture. This study proposes the injection of CO_2-saturated brine into deep basalt-andesite reservoirs, where CO_2 reacts with minerals to form stable carbonates. Based on an analogy with the CarbFix project at 100°C, this indicates rapid release of Ca^{2+} ions and carbonate formation exceeding 95% within two years. Reactive transport modelling estimates a storage capacity of 200,000 tCO_2/year (conservative scenario) to over 1 Mt/year (optimistic scenario), which could offset 80% of regional emissions. Strategically located along Indonesia's eastern maritime route, Batu Angus can utilise port infrastructure for ship-based CO_2 imports. This project aligns with Indonesia's CCS regulations (PR14/2024) and Pertamina's storage potential of ~600 Gt, positioning Indonesia as a leader in global carbon removal.

Keywords: andesitic basalt; mineral carbonation; maritime CO_2 transport; network integration; carbon carbon.

INTRODUCTION

The rise in CO_2 emissions resulting from the combustion of fossil fuels has accelerated global climate change, which continues to underscore the urgency of meeting the emission reduction targets set out in the Paris Agreement (IPCC, 2021). Carbon Capture and Storage (CCS) is widely recognised as one of the key strategies for achieving these emission targets, with an approach focused on capturing CO_2 from emission sources and storing it safely underground or in stable mineral forms (Rasool & Ahmad, 2023)

In Indonesia, Batu Angus in Ternate consists of basaltic lava flows resulting from the volcanic activity of Mount Gamalama during the historical period. This rock contains plagioclase and Ca-rich pyroxene, which are ideal for carbonation reactions. However, to date, no in situ basalt-based CCS project has been piloted in Indonesia, despite the country's highly suitable geological potential and supporting infrastructure (Irzon et al., 2024). Furthermore, the integration of CO_2 capture from power generation facilities with the cross-regional CO_2 transport supply chain remains under-discussed in the literature, particularly in the context of applying mineral carbonation to basalt in Indonesia (Nooraiepour et al., n.d.).

Among the various CCS techniques developed, in situ mineral carbonation in basalt rock is one of the most promising options. This is due to the high content of silicate minerals rich in divalent ions such as Ca^{2+}, Mg^{2+}, and Fe^{2+} in basalt, which are capable of reacting with dissolved CO_2 to form stable and permanent carbonate minerals (Raza et al., 2022). Comprehensive studies have also identified basalt as a target CO_2 storage with significant potential due to its porosity and permeability characteristics, which support chemical reactivity with CO_2, as well as the validation of mechanisms demonstrating various complex mineralisation reaction pathways.

One example of the practical application of this approach is the CarbFix Project in Iceland, which has experimentally demonstrated that over ~95% of the CO_2 injected into aqueous basalt can be converted into carbonate minerals within less than two years, thereby providing a safe and permanent form of CO_2 storage (Matter et al., 2016) These results confirm that basalt not only provides a physical medium for CO_2 placement but also offers a highly effective chemical trapping pathway through mineral carbonation.

This study aims to evaluate the technical and economic feasibility of permanent CO_2 storage via mineral carbonation in Batu Angus basalt under two CO_2 supply scenarios, namely direct capture from the Kastela Combined Cycle Power Plant and the transport of liquid CO_2 via port facilities from regional industrial emitters, as well as to assess the potential positive environmental impacts in the form of mitigation of ocean

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acidification and enhanced resilience of coral reef ecosystems due to reduced CO_2 emissions into the atmosphere and the ocean.

METHODOLOGY

This study was conducted from January to August 2024 using a hybrid research design that integrates a systematic literature review and numerical geochemical simulation to evaluate the technical and economic feasibility of CO_2 storage via mineral carbonation in the Batu Angus formation in Ternate. This approach enables the synthesis of global evidence from the scientific literature with simulation-based contextual analysis for the specific case of Indonesia, without involving primary experiments in the field or laboratory.

The study population comprises all scientific publications relating to mineral carbonation in basaltic rocks indexed in international databases, as well as secondary data on the mineralogical and geochemical characterisation of Batu Angus from previous studies. Literature samples were selected through a screening process based on eligibility criteria, whilst rock geochemical data were obtained from reputable publications employing analytical techniques such as XRD, SEM-EDS, and ICP-OES (Amalokwu et al., 2017; Belshaw et al., 2024; Matter et al., 2016).

Data collection was carried out in two main stages. First, a systematic literature review was conducted on the Scopus, Web of Science, and ScienceDirect databases using structured keywords, and the selection process followed the PRISMA guidelines to ensure transparency and reproducibility. Second, data on rock composition, hydrothermal conditions, and geochemical reaction parameters were extracted from previous research reports on Batu Angus and global analogue sites, including the CarbFix project in Iceland.

Geochemical simulations were performed using PHREEQC software version 3.7 with the llnl.dat thermodynamic database, whilst reactive transport simulations were carried out using TOUGHREACT. The model was designed to simulate batch reactions and reaction pathways between dissolved CO_2 and rock minerals, as well as rock-fluid interactions at the reservoir scale. The reliability of the model was evaluated through conceptual benchmarking against results reported in the CarbFix project and previous laboratory studies.

Data analysis techniques include thematic analysis for synthesising literature findings and quantitative analysis of simulation results. Simulation outputs were analysed using descriptive statistics and graphical visualisations, as well as parameter sensitivity tests within the range of values reported in the literature. Economic evaluation was carried out using a literature-based cost–benefit approach, whilst environmental impacts were assessed semi-quantitatively based on the empirical relationship between CO_2 emission reductions and ocean acidification mitigation.

RESULTS AND DISCUSSION

Global CO_2 emissions continue to rise and have reached record levels of tens of gigatonnes per year. For example, the Global Carbon Budget (2023) reports a growth rate of fossil CO_2 emissions of around 0.5% per year for the decade 2013–2022, still far from the rate of reduction required to meet the Paris Agreement targets (Friedlingstein et al., 2023). Over the period 1870–2019, total cumulative CO_2 emissions have reached approximately 2,035 Gt (Matter et al., 2025). To limit global temperature rise to below 2°C (ideally 1.5°C as per the Paris Agreement), drastic emission cuts are required; for instance, *the remaining 'carbon* budget' is only around 275–1,150 Gt CO_2 depending on the level of warming (Friedlingstein et al., 2023). This requirement highlights the urgency of mitigation actions and carbon capture technologies such as CCS.

Carbon Capture and Storage (CCS) is one of the main approaches to reducing atmospheric CO_2 concentrations. By 2023, over 40 industrial-scale CCS projects were operational globally, with a capture capacity of around 50 Mt CO_2/year (e.g., 41 projects totalling 49 Mt). Nevertheless, IEA analysis indicates that the capacity in place by 2030 (approximately 435 Mt/year as announced) still amounts to only ~40–60% of the ~1 Gt CO_2/year target required for a carbon-neutral scenario. Therefore, while CCS is considered technically

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effective for long-term carbon storage and reducing the risk of leakage, its current scale of implementation is insufficient to meet global climate targets.

Basalt deposits are widespread (covering around 10% of the Earth's land area) and are generally rich in Ca, Mg and Fe minerals that react with CO_2 (IEA GHG R&D Programme, 2017). Indonesia itself lies on an active subduction zone and has many basaltic provinces (for example in Sumatra, Java, Sulawesi, Maluku and Papua), giving it geological potential as a site for mineral carbonation-based carbon storage. By way of illustration, local studies in Indonesia indicate MgO and CaO contents in basalt/basaltic rocks across various regions (e.g. 0.7–3.9% MgO and 2.8–15% CaO), comparable to basalt at global pilot sites. Given similar mineralogical conditions, the basalt rocks at Batu Angus, Ternate, have the potential to replicate CO_2 storage performance through mineral carbonation, as demonstrated in global projects.

Basalt rocks are rich in silicate minerals containing divalent cations (Ca^{2+}, Mg^{2+}, Fe^{2+}) that are highly reactive with carbonic acid (dissolved CO_2). For example, plagioclase (anorthite) as well as pyroxene and olivine in basalt provide sources of Ca, Mg, and Fe for the formation of carbonate minerals. Upon contact with CO_2-acid solutions, these cations are released into solution and immediately precipitate as stable carbonates (calcite, magnesite, siderite). Thus, basalt is chemically capable of 'locking' CO_2 as permanent carbonate minerals (Romano et al., 2024).

Petrographic data and XRD analysis of Batu Angus indicate an abundance of calcium-rich plagioclase of 28–36% and clinopyroxene of 12–18%, which provide an abundance of divalent cations (Ca^{2+}, Mg^{2+}, Fe^{2+}) as the primary elements in the process of permanently trapping CO_2 within minerals. Laboratory analogue experiments on Indonesian andesite rocks (Belshaw et al., 2024) reported total rock dissolution rates of 2.4×10^{-11} to 4.2×10^{-11} mol m^{-2} s^{-1} at 100 °C, capable of releasing sufficient cations to support rapid carbonate mineral formation. The CarbFix field trial in Iceland also demonstrated that over 95% of the injected CO_2 was successfully mineralised within 1–2 years under similar geochemical conditions. Projections of CO_2 storage capacity and injection scenarios based on this analogy are presented in Table 1.

Table 1. CO_2 Storage Capacity Projections and Injection Scenarios

Scenario	Annual CO_2 Input (t/y)	Source Mix	Mineralisation Efficiency (2 years)	CO_2 Stored (t/y)
Conservative	200,000	110,000 tonnes from the Kastela Combined Cycle Power Plant + 90,000 tonnes shipped	85%	170,000
Accelerated	1,000,000	PLTMG + regional ship CO_2 aggregation	95%	950,000

The economic projections and Break-Even Point (BEP) estimates for both injection scenarios are summarised as shown in Table 2.

Table 2. Economic Projections and Break-Even Point Estimates

Throughput (t CO_2/y)	CarbonPrice (USD/t)	Gross Revenue (USD/year)	Gross Revenue (IDR/y)	Break-even point Timeline
200,000	30	6,000,000	~90 billion	8–9 years
1,000,000	30	30,000,000	~450 billion	4–5 years

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Several large-scale field projects have demonstrated the efficiency of mineral carbonation in mafic and ultramafic rocks:

1. CarbFix (Iceland): Reports that by injecting dissolved CO_2 into basalt formations at a depth of ~500 m, more than 95% of the injected CO_2 had been sequestered as minerals within less than 2 years (Matter et al., 2016).
2. Wallula Basalt Pilot (US): Core samples were taken following the injection of ~1,000 tonnes of CO_2 into basalt and found that approximately 60–65% of the CO_2 had mineralised within 2 years, with carbonates (e.g. ankerite) filling ~4% of the formation's porosity (McGrail et al., 2017; White et al., 2020).
3. Oman Peridotite: results of CO_2 injection into ultramafic peridotite, showing ~88% of CO_2 bound as carbonate in just ~45 days (Matter et al., 2025).

Geochemical simulation methods are frequently used to predict carbonation reactions. Software such as PHREEQC (for batch and 1D modelling) and TOUGHREACT (for 3D reactive flow simulation) has been specifically developed for fluid-rock interactions

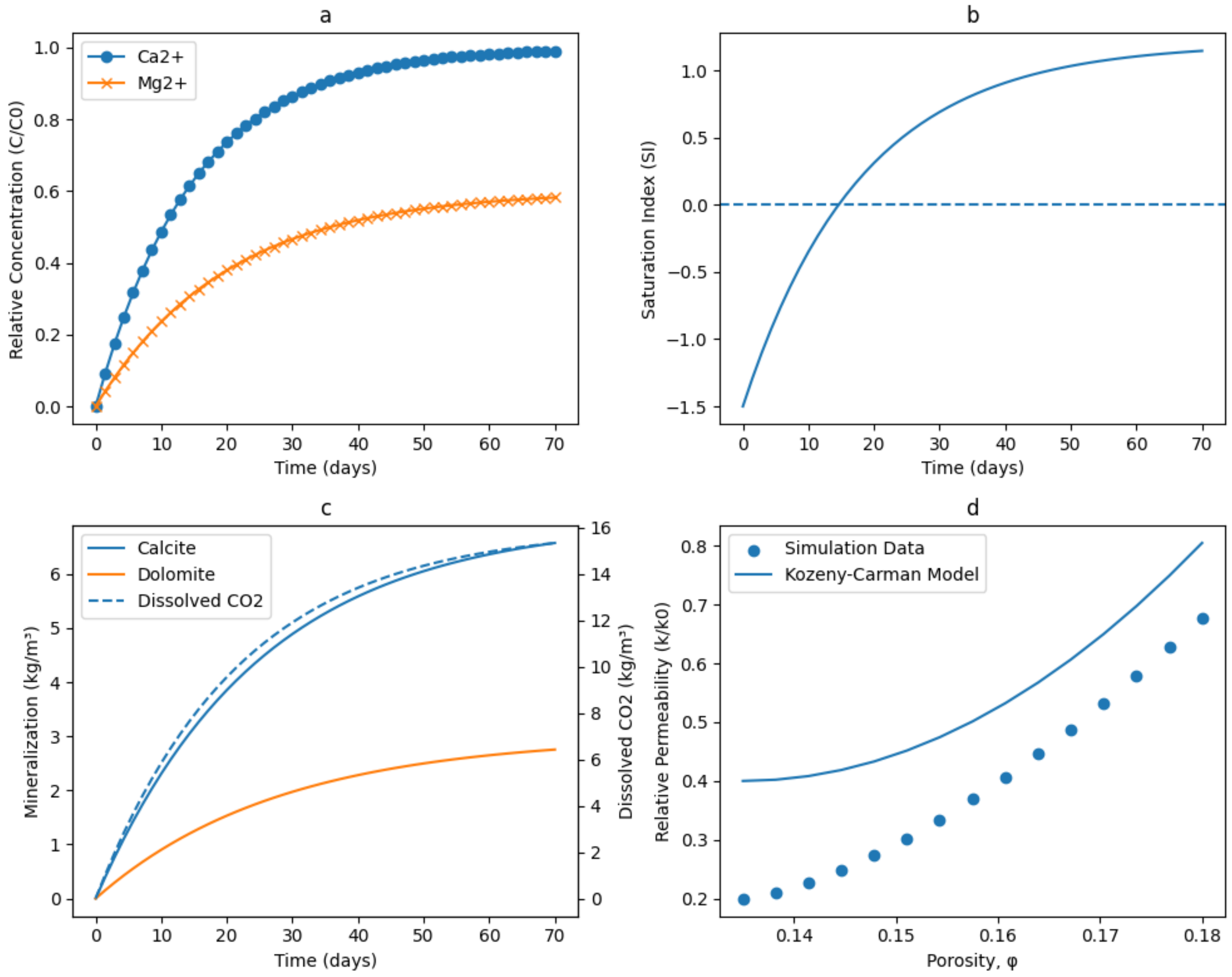

Figure 1. PHREEQC and TOUGHREACT simulations: (a) evolution of Ca^{2+} and Mg^{2+} concentrations over time; (b) changes in the calcite saturation index during the simulation; (c) rate and accumulation of CO_2 mineralisation; (d) decrease in and reservoir permeability due to secondary mineral precipitation.

Geochemical simulation results using PHREEQC over 70 days indicate that the Batu Angus CO_2–basalt system undergoes three main reaction stages consistent with the mechanism of mineral carbonation in mafic rocks.

1. In the initial phase (days 0–20), intensive dissolution of primary silicate minerals occurred, marked by an increase in the concentration of Ca^{2+} and Mg^{2+} in the solution. This process was triggered by a decrease in pH due to the formation of carbonic acid from dissolved CO_2. The calcite saturation index (SI), which was initially negative (−1.5), indicates an undersaturated condition, meaning that mineral dissolution was more dominant than precipitation.
2. Entering the second phase (days 20–50), there was a significant increase in the calcite saturation index, reaching
   +1.2, indicating that the system had become supersaturated with carbonates. At this stage, calcite and magnesite precipitation became the dominant mechanism, with total CO_2 mineralisation reaching 17.15 kg/m³, comprising 7.02 kg/m³ of calcite and 3.30 kg/m³ of magnesite. The decrease in Ca^{2+} and Mg^{2+} concentrations in the simulation results table confirms that these ions were consumed in the formation of secondary carbonates.
3. In the final phase (days 50–70), the system showed a tendency towards conditions approaching steady-state. The rate of pH change slowed and dissolved ion concentrations stabilised, indicating a reduction in the reaction driving force. This pattern is consistent with reaction kinetic limitations and a decrease in reactive surface area due to the coating of secondary minerals.

Overall, the average carbonation rate of 0.245 kg CO_2/m³/day indicates relatively high performance compared to field studies at Wallula, yet remains within a realistic range for systems at higher temperatures (100°C). This underscores the role of temperature in accelerating the kinetics of silicate dissolution and carbonate precipitation. Reactive transport simulations using TOUGHREACT show that carbonate precipitation has a direct impact on changes in the physical properties of the reservoir. The simulation results table shows a 4.2% decrease in porosity from the initial conditions, following an exponential trend consistent with the accumulation of secondary minerals.

This decrease in porosity was accompanied by a reduction in permeability of up to 76%, calculated using the Kozeny–Carman approach. The non-linear relationship between porosity and permeability indicates that, although the change in pore size is relatively small in absolute terms, its impact on fluid flow is quite significant. Nevertheless, the final permeability remains within the operational range for industrial-scale CO_2 injection, meaning the system has not yet experienced total clogging. This situation highlights a trade-off between the safety of permanent storage (mineral trapping) and long-term injection capacity.

CONCLUSION

This study evaluates the potential for CO_2 mineral carbonation in the Batu Angus basalt-andesite formation, Ternate, using geochemical simulation (PHREEQC) and reactive transport (TOUGHREACT) approaches based on literature parameters from global projects. Simulation results show that over a 70-day period at 100°C and pressures of 10–15 bar, the system is capable of mineralising up to 17.15 kg CO_2/m³ through the formation of secondary carbonates, primarily calcite (7.02 kg/m³) and magnesite (3.30 kg/m³).

The reaction evolution reveals three main stages: dissolution of primary silicates in the initial phase, dominant carbonate precipitation in the intermediate phase, and a trend towards steady-state conditions in the final phase. The increase in the calcite saturation index from −1.5 to +1.2 confirms the system's transition from an undersaturated to a supersaturated state with respect to carbonates.

Reactive transport simulations indicate that the precipitation of secondary minerals causes a 4.2% reduction in porosity and a decrease in permeability of up to 76%, following the non-linear Kozeny–Carman relationship. Despite the decline in flow properties, the final permeability value remains within the operational range for CO_2 injection, indicating a balance between the safety of permanent storage (mineral trapping) and long-term injection capacity.

However, these results are still simulated and depend on assumptions of reservoir homogeneity and

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literature-based kinetic parameters. Further studies involving petrophysical characterisation and experimental reactivity tests are required to comprehensively validate field feasibility.

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REFERENCES

Amalokwu, K., Papageorgiou, G., Chapman, M., & Best, A. I. (2017). Modelling ultrasonic laboratory measurements of the saturation dependence of elastic modulus: New insights and implications for wave propagation mechanisms. *International Journal of Greenhouse Gas Control*, *59*, 148–159. https://doi.org/10.1016/j.ijggc.2017.02.009

Belshaw, G. E., Steer, E., Ji, Y., Azis, H., Sapiie, B., Muljadi, B., & Vandeginste, V. (2024). Fluid-rock interaction experiments with andesite at 100°C for potential carbon storage in geothermal reservoirs. *Deep Underground Science and Engineering*, *3*(3), 369–382. https://doi.org/10.1002/dug2.12097

Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Bakker, D. C. E., Hauck, J., Landschützer, P., Le Quéré, C., Luijkx, I. T., Peters, G. P., Peters, W., Pongratz, J., Schwingshackl, C., Sitch, S., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S. R., Anthoni, P., … Zheng, B. (2023). Global Carbon Budget 2023. *Earth System Science Data*, *15*(12), 5301–5369. https://doi.org/10.5194/essd-15-5301-2023

IEA GREENHOUSE GAS R&D PROGRAMME Review of CO_2 Storage in Basalts. (2017). www.ieaghg.org

Irzon, R., Hanang Samodra, & Sam Permanadewi. (2024). Prospecting for a CCS Project in Indonesia: A Case Study in the Meratus Mountains, South Borneo. *Journal of Geology and Mineral Resources*, *25*(1), 31–40. https://doi.org/10.33332/jgsm.geologi.v25i1.784

Matter, J. M., Speer, J., Day, C., Kelemen, P. B., Ibrahim, A., Mani, S. Al, Tasfai, E., Ilyas, M., Khimji, K., & Hasan, T. (2025). Rapid mineralisation of carbon dioxide in peridotites. *Communications Earth and Environment*, *6*(1). https://doi.org/10.1038/s43247-025-02509-5

Matter, J. M., Stute, M., Snæbjörnsdottir, S., Oelkers, E. H., Gislason, S. R., Aradottir, E. S., Sigfusson, B., Gunnarsson, I., Sigurdardottir, H., Gunnlaugsson, E., Axelsson, G., Alfredsson, H. A., Wolff-Boenisch, D., Mesfin, K., Taya, D. F. D. L. R., Hall, J., Dideriksen, K., & Broecker, W. S. (2016). Rapid carbon mineralisation for the permanent disposal of anthropogenic carbon dioxide emissions. *Science*, *352*(6291), 1312–1314. https://doi.org/10.1126/science.aad8132

McGrail, B. P., Schaef, H. T., Spane, F. A., Horner, J. A., Owen, A. T., Cliff, J. B., Qafoku, O., Thompson, C. J., & Sullivan, E. C. (2017). Wallula Basalt Pilot Demonstration Project: Post-injection Results and Conclusions. *Energy Procedia*, *114*, 5783–5790. https://doi.org/10.1016/j.egypro.2017.03.1716

Nooraiepour, M., Masoudi, M., Haile, G., & Hellevang, H. (n.d.). *Intricacies of CO_2–Basalt Interactions, Reactive Flow and Carbon Mineralisation: Bridging Numerical Forecasts to Empirical Realities*.

Rasool, M. H., & Ahmad, M. (2023). Reactivity of Basaltic Minerals for CO_2 Sequestration via In Situ Mineralisation: A Review. In *Minerals* (Vol. 13, No. 9). Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/min13091154

Raza, A., Glatz, G., Gholami, R., Mahmoud, M., & Alafnan, S. (2022). Carbon mineralisation and geological storage of CO_2 in basalt: Mechanisms and technical challenges. In *Earth-Science Reviews* (Vol. 229). Elsevier B.V. https://doi.org/10.1016/j.earscirev.2022.104036

Romano, P., Brusca, L., & Liotta, M. (2024). Element mobility during basalt-water-CO_2 interaction: observations in natural systems versus laboratory experiments and implications for carbon storage. *Geochemical Transactions*, *25*(1). https://doi.org/10.1186/s12932-024-00087-7

White, S. K., Spane, F. A., Schaef, H. T., Miller, Q. R. S., White, M. D., Horner, J. A., & McGrail, B. P. (2020). Quantification of CO_2 mineralisation at the Wallula Basalt Pilot Project. *Environmental Science and Technology*, *54*(22), 14609–14616. https://doi.org/10.1021/acs.est.0c05142

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