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Recent Advances in Olivine-Based Adsorbents for Water Treatment: A review

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Abstract

The scarcity of fresh water resources is one of the biggest challenges encountered in the world. To address this challenge, water treatment and reuse may provide an alternative solution to increase water availability and alleviate the burden on governments. Adsorption is an effective and economical water treatment method that can be applied for the removal of contaminants from water. Naturally available and low-cost materials such as olivine have shown promising results as adsorbents for removing diverse contaminants in water purification. Olivine is one of the most abundant minerals on Earth, comprising more than 50 % of the Earth's upper mantle. It is a low-cost material that has shown a promising potential as an adsorbent material. This short review summarizes the potential applications of olivine as an adsorbent for water purification applications in the removal of a variety of contaminants from water. The adsorption mechanisms proposed for olivine as an adsorbent in water treatment applications are summarized. Furthermore, other uses of olivine in the field of environmental remediation are also listed. The future prospects for the use of olivine in the field of water treatment are finally outlined. This topic is relevant and timely, given the increasing demand for sustainable materials in water purification applications.

Paper type: Review Article

Keywords: Olivine, adsorption, Mechanisms, Water treatment, Environmental remediation

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1. Introduction

Adsorption is one of the most effective and economical remediation methods for purifying water and wastewater from organic and inorganic pollutants (Satyam and Patra, 2024). Adsorption can be defined as a process in which an adsorbate (pollutant) from a gas or a liquid phase is bound to the surface of a solid phase (adsorbent) when the adsorbate is brought into contact with the solid phase (Saleh, 2022). Various adsorbent materials have been developed for effective water purification from clays, zeolites, biochar, activated carbon, polymers, and nanomaterials (Sahu et al., 2024). Among these materials, activated carbon (AC) is widely used because of its high surface area, porosity, and affinity for organic compounds. However, AC has some drawbacks, such as its high cost, low selectivity, and difficulty in regeneration (Satyam and Patra, 2024). Therefore, efforts are constantly directed towards exploring other types of low-cost adsorbents. Non-metallic ores in Jordan, including diatomite (Al-Qodah et al., 2007, Qada, 2019), zeolite and kaolin (Nadeen Alsmadi 2024) have been used in various applications such as water treatment. Another non-metallic ore in Jordan is basalt. This rock contains olivine as a major mineral. Olivine has been reported to be a cost-effective adsorbent in water purification applications.

Olivine is a naturally occurring mineral that makes up approximately 50% by volume of the Earth's mantle. The mantle, which consists primarily of a layer of silicate rock between the crust and the outer core, comprises about 67% of the Earth's mass (Lodders and Fegley, 1998). Olivine is a magnesium iron silicate with the formula $(Mg^{2+},Fe^{2+})_2SiO_4$ and has an orthorhombic crystal system (Liu et al., 2024). The crystal structure of olivine consists of isolated SiO4−4 tetrahedra bound via ionic bonds to octahedrally coordinated cations, such as ~~Mg^{2+} (forsterite, Mg_2SiO_4)~~ (van Genuchten et al., 2023) (Figure 1). Olivine exhibits a complete isomorphic series between its Mg-

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and Fe-rich end members. There are no oxygen atoms bonding Si with Mg, therefore, Mg^{2+} can be easily detached from the olivine surface during dissolution (Liu et al., 2024). The dissolution rate of olivine depends on many factors such as: pH, water activity, temperature, and mineral-fluid interfacial surface area (Oelkers et al., 2018).The dissolution of Mg-rich olivine (forsterite) can be represented by Eq. (1) (Rimstidt et al., 2012):

$$Mg_2^{[6]}Si^{[4]}O_4^{[4]} + 4H^+ + 12H_2O \rightarrow 2(Mg.6H_2O)^{2+} + Si(OH)_4 \quad (1)$$

where the superscripts in the square brackets represent the coordination numbers of the atoms, i.e., the number of atoms, molecules or ions bonded to it. It can be seen from the equation that the dissolution of forsterite is not purely a bond fracturing process, but rather it entails bond rearrangements. During the dissolution process, each of the six Mg–O bonds in forsterite is replaced by a Mg–OH2 bond to produce a Mg ion coordinated by six water molecules. Each of the four SiO–Mg^3 bonds becomes a SiO–H bond to form an aqueous silica species. Therefore, the dissolution of olivine enhances seawater alkalinity. In addition, the dissolution of silicate-containing minerals like olivine is one of the approaches used for carbon dioxide removal. This process is considered a part of the Earth's carbon cycle through carbon dioxide sequestration from the atmosphere. This reaction can be represented by Eq. (2) as follows (Liu et al., 2024):

$$(Mg, Fe)_2SiO_4 + 4H_2O + 4CO_2 \rightarrow 2(Mg^{2+}/Fe^{2+}) + 4HCO_3^- + H_4SiO_4 \quad (2)$$

When carbon dioxide dissolves in water, it produces carbonic acid, bicarbonate ions, and carbonate ions, where the relative proportions of which depends on the pH. The Mg^{2+} ions then react with bicarbonate and carbonate ions to form carbonate minerals which precipitate at high saturation levels. In addition, the silicic acid (H_4SiO_4) likely precipitates as hydrated amorphous silica (SiO_2(am)) in low temperature systems (Johnson et al., 2014).

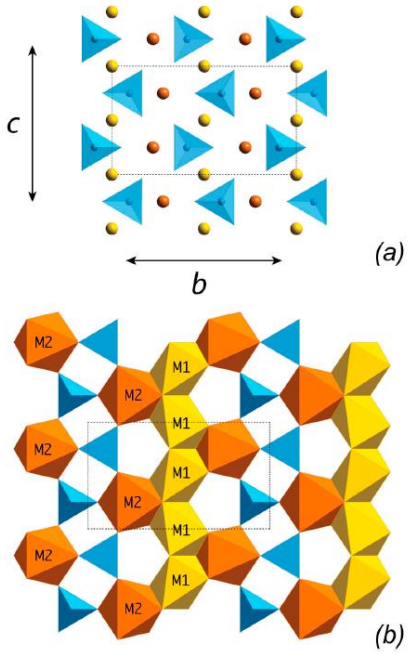

Fig. 1. Projected olivine structure down the a-axis of the orthorhombic unit cell. a) Arranged two planes of an isolated SiO4 tetrahedra aligned along the b and c axes and pointing alternately up and down along c; M1 and M2 are the cations colored in yellow and orange, respectively. b) Geometric distribution of M1 and M2 octahedra relative to the SiO4 tetrahedra on a single plane of the unit cell. Adapted from (Oelkers et al., 2018) with permission.

The potential of olivine as an adsorbent in water treatment systems to remove a range of contaminants from aqueous solutions has been lately investigated through a number of studies that have attempted to delve deeper into the mechanisms by which olivine adsorbs contaminants from water. For instance, a number of studies have explored the potential of olivine to remove heavy metals from water (Wium-Andersen et al., 2012, Monrabal-Martinez et al., 2017, van Genuchten et al., 2023). The removal of metals was reported to be positively correlated with the solution pH. In addition, it also resulted in an increase in the solution pH (Wium-Andersen et al., 2012, Kleiv and Thornhill, 2004, van Genuchten et al., 2023). (van Genuchten et al., 2023) attributed these observations to the decreased solubility of heavy metals associated with the increased solution pH which promotes the precipitation of metal oxides (oxyhydroxides),

carbonates and silicates. Other studies have prepared composite adsorbents from olivine by the impregnation of metals such as aluminum or iron in the form of complex silicate, oxides, and hydroxides into the raw olivine followed by a calcination step and tested them to remove metal ions such as fluoride and arsenic from water (Ghosal Partha and Gupta Ashok, 2018, Ghosal et al., 2018). Other studies have used olivine as a filtering material to remove natural organic matter (McMeen and Benjamin, 1997) and amino acids from water (Cruz-Hernández et al., 2022).

This paper reviews the potential applications of olivine as an adsorbent for water purification from various contaminants present in water and wastewater streams. The chemical and physical properties of olivine are discussed. It also lists the adsorption mechanisms proposed by researchers and summarizes all the studies that employed olivine as an adsorbent for water treatment applications. Case studies of the use of olivine as an adsorbent are also discussed. Furthermore, other uses of olivine in the field of environmental remediation are outlined. Finally, future prospects and gaps for olivine research in the field of water treatment are proposed.

2. Chemical and Physical Properties of Olivine

The name 'olivine' was given by A.G. Werner in 1790, in reference to the common olive-green color. However, the name is now used as a group name (King, 2009). Olivine is a major component of many mafic and ultramafic igneous rocks, and its Mg/Fe ratio is lower in the more developed gabbros and basalts. In metamorphic rocks, Mg-rich (forsterite) and Fe-rich (fayalite) compositions are found, and it is also found in the gradual metamorphism of serpentinites. It is characterized by high protrusion, high birefringence, and the absence of well-developed cleavage. Olivine varies in composition from Mg_2SiO_4 (forsterite) to Fe_2SiO_4 (fayalite), where there is a complete solid solution between Mg^{2+} and Fe^{2+} in the structure. In many natural crystals, especially in the more iron-rich peridotites, slight substitution of (Mg, Fe) by Mn and Ca occurs. Nickel and chromium are common in magnesium-rich peridotites, but chromium is more common in fine melted chromite plates. Some Fe3+ is usually present and may be similarly associated with small melted grains of magnetite or more commonly with an oxidation product formed by the alteration of peridotite. Relatively small amounts of calcium exist in most peridotites, with the normal range being 0.01.0% by weight of CaO. Phosphorus is present in trace amounts (up to 400 ppm) in some peridotites, where the charge balance is preserved by octahedral site vacancies (Deer et al., 2013). Since olivine consists of two main structural units: silicate tetrahedra SiO_{4-4} and metal cations (Mg^{+2} and/or Fe^{+2}), its adsorption performance depends mainly on its chemical reactivity, especially with CO2 and some heavy metals, as will be discussed in next sections. **Table 1** shows the typical chemical composition of olivines from different origins. According to the table, Norwegian olivine has the highest magnesium oxide content and the lowest iron content, making it ideal for refractory applications. The low loss on ignition (LOI) ratio also reflects that the material is less susceptible to alteration. The magnesium oxide and silicon oxide (SiO_2) component of this olivine is approximately 89–93% by weight, indicating the high purity of the mineral. On the other hand, Indian olivine has the lowest magnesium oxide content and the highest iron content. The high LOI also indicates a greater potential for alteration.

Olivine has many advantages such as low heat conductivity (0.031 cal/cm/sec/°C) and good insulating characteristics, high refractoriness (fusion point of 1700-1760 °C) due to high forsterite content (melting point of 1890 °C), which also gives resistance to reaction with molten metals and slag resulting in a longer life, low thermal expansion of 0.8 % at 1000 °C resulting in thermal shock resistance, high volume heat capacity (specific heat between 20 and 1000 °C is 0.23 to 0.3 cal/g/°C), useful as a heat storage material, high abrasion resistance where Moh's scale hardness is 6.5-7. In addition, it has a specific gravity of 3.26-3.4 and a bulk density of 1.5-2.0 g.cm-3 (Sarkar, 2002). The isoelectric point of olivine ranges from above 3 to about 5, at which point the net charge of the olivine surface becomes zero. While at pH values above the isoelectric point, the surface of olivine is mostly negatively charged (Liu et al., 2024). Furthermore, as olivine is a hard material that is not easily ground, the surface area depends on the activation method used to prepare and increase the activity of the olivine (Summers et al., 2005). For instance, one study combined dry mechanical activation of olivine followed by wet milling to produce specific surface area at rates exceeding that obtainable by wet milling alone. In that study, a value of 26.28 ± 1.28 m2/g was reported after 30 min of wet milling in a planetary mill, while 25 min of dry mechanical activation followed by 5 min of wet milling yielded a specific surface area of 64.44 ± 2.13 m2/g (Kleiv and Thornhill, 2016). In comparison, the specific surface area of unmodified olivine varies depending on its particle size and form. For example, the surface area for crushed olivine (San Carlos, Arizona) with a grain size ranging from 250 to 500 μm was estimated in one study to be 0.05 m^2/g (Brantley and Mellott, 2000).

Clearly, the above-mentioned properties are related to the adsorption performance of olivine. For example, the hardness of the material plays a role in its durability during use and its susceptibility to erosion. Furthermore, it affects processes such as grinding. Conversely, thermal stability indicates how the material reacts during processing or activation processes, and whether it can be used in high-temperature applications, such as flue gas adsorption/filtration. The surface area is directly tied to the adsorption capacity as more surface area results in more interactions with the pollutant molecules and faster kinetics. In contrast, the structure of the material

determines the active sites available for adsorption and whether they are stable and accessible, as is the case when comparing layered/open structures versus dense structures (Natarajan et al., 2022).

Table 1.Typical chemical composition of different olivines (wt %). Adapted from (Sarkar, 2002) with permission.

	"Norway (Aaheim)"	**"USA (Carolina)"**	**"China"**	**"Russia (Kuznetsk Ala Tau)"**	**"India (Salem)"**
SiO_2	41-43	41.5-43	40-44	42-44	38-40
Al_2O_3	< 1.0	< 0.5	< 1.0	1-1.5	2-3
Fe_2O_3	6.8-7.4	8-9	7-10	8-10	11-13
CaO	< 0.5	< 0.5	< 0.4	< 0.5	trace
MgO	48-50	46-48	44-48	43-45	42-45
LOI	0.5-1.2	0.8-1.4	< 3.0	2-3	< 3.0

3. Mechanisms of Adsorption onto Olivine

Good adsorbent materials are those materials having high selectivity, high adsorption capacity, long run-life and low price. Different adsorbents have different properties depending on their active surface, pore size, pore size distribution, surface area, and surface functional groups (Pourhakkak et al., 2021). These properties can be obtained through different characterization techniques, the choice of which depends on the type of material to be studied and the equipment available. Examples of these techniques include FTIR, Raman, XPS, EDX, zeta potential, XRD, SEM, TEM, AFM, surface area and porosity, and thermogravimetric analysis (TG, DTA, DSC, DTG), among many others (Pellenz et al., 2023). These characterization techniques are essential in identifying the surface and structural features that influence the adsorption performance.

Adsorption is usually described as physisorption or chemisorption according to the strength of the interaction between the adsorbent and the adsorbed pollutant (i.e., adsorbate) (Sims et al., 2019). In the physical adsorption, also known as physisorption, the bonding between the adsorbate and the adsorbent occurs via weak electrostatic interactions including Van der Waals interactions, dipole-dipole and London forces. No changes occur in the chemical structure of either the adsorbate or the adsorbent (Alaqarbeh, 2021). These weak interactions between the physically adsorbed adsorbate and the adsorbent typically range from 0.2 to 4 kJ/mol. This type of bonds are the weakest type of interactions and can be easily fractured (Cottrell, 1954). In comparison, in the chemical adsorption, also named chemisorption, a chemical bond is formed between the adsorbate and the adsorbent, by rearranging the electron density between the two of them. The nature of this bond is either ionic or covalent (Alaqarbeh, 2021). It is worth noting that the strength of the hydrogen-bonding interactions falls between the strength of the physically adsorbed and the chemically adsorbed species, i.e., at 12–30 kJ/mol. However, it is usually described as a physisorbed interaction (Cottrell, 1954). The key differences between the physical and chemical adsorption such as the nature of bonding, reversibility, and activation energy are summarized in **Table 2.**

The interactions interplaying between the adsorbate and the adsorbent depend on the surface charge and functional groups of the two materials. In addition, classical models such as Langmuir, Freundlich, Redlich–Peterson (RP), Sips, and Dubinin–Radushkevich isotherms have been employed to elucidate the mechanisms of adsorption at equilibrium (Wang and Guo, 2020). However, these models are based on simple assumptions and suffer from some limitations such as the difficulty of microscopic interpretation of the adsorption process (Ghorbali et al., 2024). To overcome these limitations, advanced statistical physics models have been introduced to better understand the mechanisms of adsorption and provide more insights into the behavior of the adsorbent-adsorbate systems at the molecular level (Djama et al., 2023). These models are based on parameters that are associated with properties with physical meaning in the adsorption process. These parameters are classified into three classes: steric parameters, energetic parameters, and Van der Waals parameters (Amrhar et al., 2021). Examples of the advanced statistical physics models include monolayer model (Ghorbali et al., 2024), double-layer model (Wang et al., 2023), and multilayer model (Hanafy et al., 2020).

Table 2. Differences between physical and chemical adsorption. Adapted with permission from (Alaqarbeh, 2021).

Criteria	Physical Adsorption	Chemical Adsorption
Specificity	Non-specific	Highly-specific
Nature of adsorption	Depend on nature of adsorbent	Depend on nature of adsorbent
Reversibility	Reversible process	Mainly irreversible
Enthalpy	Low (20-40 kJ/mol)	Higher than physical adsorption (40-300 kJ/mol)
Activation energy	Does not require high activation energy	Require high activation energy
Layer of adsorption of interfacial region (saturation)	Multi layers	Mono layer
Bonding	Week Van der Waals, London forces, and dipole-dipole attraction. This attraction has longer range than chemical type, and there is no chemical composition change for substrate	Strong ionic bond, or covalent bond formed between substrate and adsorbent, there is a chemical composition change. This attraction has shorter range than the physical type

Olivine has been used to remove a variety of pollutants from water including metal ions (van Genuchten et al., 2023), pharmaceuticals (Al-Rawajfeh et al., 2022), natural organic matter (NOM) (McMeen and Benjamin, 1997), and amino acids (Cruz-Hernández et al., 2022). Various mechanisms have been proposed to explain the adsorptive removal efficiency (RE%) of olivine toward various contaminants in water. Most natural, river and lake waters have a pH value in the range of 6–9 (Gałuszka and Migaszewski, 2020). As mentioned in the previous section, olivine at these pH conditions is negatively charged. Thus, (Cruz-Hernández et al., 2022) have attributed the removal of positively charged amino acids by olivine to the electrostatic interactions at the pH conditions under which amino acids are positively charged and olivine surfaces are negatively charged. Others have proposed a substitution mechanism of magnesium ions by cations of various metals (Hayrapetyan et al., 2023), or ion exchange mechanism between the metal ions and the magnesium ions present in the structure of olivine (Chen et al., 2025). Another study described the nature of the adsorption of paracetamol (a pharmaceutical drug) to olivine as physical adsorption (physisorption), mainly due to Van der Waal's forces and hydrogen bonding (Al-Rawajfeh et al., 2022). In other studies, the adsorption mechanism has been described as a monolayer chemisorption type of mechanism for metals ions adsorbed onto the surface of olivine (Pourhakkak et al., 2021, Kleiv and Thornhill, 2004).

In addition to the mechanisms of adsorption of metal ions onto the surfaces of olivine particles, other mechanisms have been suggested which ascribed the removal of metal ions by olivine to an alternative pathway based on olivine dissolution. In this second pathway, aqueous SiO_4^{-4} is produced from Mg_2SiO_4 weathering. The newly formed aqueous SiO_4^{-4} consumes H^+ to form H_4SiO_4 (equation 2), resulting in high pH conditions that favor the make up of secondary metal oxides (oxyhydroxides), carbonates or silicates, based on the accompanying metal ions (van Genuchten et al., 2023). **Table 3** below shows various studies in the literature that have used olivine in water treatment applications. As such olivine can be considered unique amidst adsorbent materials, as it chemically reacts with CO_2 to form stable magnesium/iron carbonates, neutralizes acidity, immobilizes toxic metals such as Cd^{+2}, pb^{+2} and Ni^{+2}, and it is an ecofriendly material that has no negative impact om the environment. However, further studies are still lacking to gain deeper insights into the adsorption mechanisms and the selectivity of olivine towards various pollutants that are present in wastewater.

Table 3. Summary of the list of studies that used olivine as an adsorbent for water treatment.

Adsorbate	Adsorbent	Removal mechanism	Removal performance	Adsorbate solution conditions (mg/L)	Temperature (°C)	Ref.
Cd^{2+}	Co-milled olivine with magnesite	Ion-exchange between Cd^{2+} and Mg^{2+} as in the form of $CdCO_3$	q_e = 270.61 mg/g	100 mg/L	Room temperature	(Chen et al., 2025)
Cu^{2+}	MgO-modified olivine composite (MgO@PO400)	Monolayer chemisorption, ion exchange, surface precipitation and electrostatic attraction	q_{max} = 225.82 mg/g, RE% of (84.95–98.05%)	pH range of 3–5.5 and associated with various accompanying ions in the water	-	(Zhou et al., 2025)
As (III) or As (V)	Fe/olivine composite prepared through wet impregnation and subsequent	Monolayer sorption mechanism mostly resembled to chemisorption	q_{max} = 2.831, for As (III) and q_{max} = 5.249, for As (V)	-	-	(Ghosal et al., 2018)

	calcination					
F^{-1}	Al/olivine composite prepared by wet impregnation and subsequent calcination	Described as aluminum-fluoride interactions	q_e = 4.88	10 mg/L	10	(Ghosal Partha and Gupta Ashok, 2018)
Cu^{2+}	Forsterite olivine (Mg_2SiO_4)	Chemisorption	-	-	-	(Kleiv and Thornhill, 2004)
Four dissolved metals: Cu, Pb, Ni and Zn in stormwater	Filters consisted of sand and three other adsorbents: (pine bark, olivine, and charcoal)	-	$q_{e,Zn}$ = 2.5 $q_{e,Cu}$ = 1.1 $q_{e,Ni}$ = 2.4, all in mg/Kg	For Zn= 18, for Cu=13.5, for Ni= 2.32, all in μg/L	Room temperature (20 ± 2)	(Monrabal-Martinez et al., 2017)
Heavy metals (Li, Na, Mg, K, V, As, Sr, Mo, Ba)	Olivine (non-treated and acid treated)	Substitution of magnesium ions by cations of various metals	$q_{max, K+}$= 30 for non-treated and = 8 for acid-treated, $q_{max, Sr}2+$= 7-8 for both, $q_{max, Mo3+}$= 0.9 for non-treated and = 3.2 for acid-treated, all in μg/g	For k^+ = 50-720	-	(Hayrapetyan et al., 2023)
Various metal contaminants (Co, Ni, Cd, Zn, Cu, Pb)	Olivine	Metal removal tool place by secondary precipitation of distinct metal carbonates and silicates, which was enhanced by increasing pH	RE% up to > 90%	-	-	(van Genuchten et al., 2023)
Amino acids (glycine, lysine, histidine, arginine, and aspartic acid)	A natural komatiite, a simulated komatiite, and the minerals: olivine, pyroxene, and plagioclase	Under pH conditions where amino acids are positively charged and mineral surfaces are negatively charged: electrostatic forces, while between similarly charged surfaces by the formation of organometallic complexes	q_e = 3.18 ×10^{-5}-2.11 ×10^{-4} (in mmol/mg)	-	Room temperature (22)	(Cruz-Hernández et al., 2022)
NOM	Iron oxide-coated olivine	Biodegradation combined with sorption into the biological and biogenic material in the schmutzdecke and deeper in the bed	q_e = 6 mg/L	7.9	21	(McMeen and Benjamin, 1997)
Paracetamol (a pharmaceutical drug)	Olivine	Physisorption (Van der Waal's interactions and hydrogen bonding)	Maximum RE% of 97.12 % at 60 min, 0.5 g of olivine, and under ultrasonic waves	-	-	(Al-Rawajfeh et al., 2022)

4. Case studies of the Use of Olivine in the Adsorptive Removal of Contaminants from Water

(van Genuchten et al., 2023) have used olivine in two solid forms: powdered olivine (PO) and granulated olivine (GO) for removing metal contaminants including: (Co, Ni, Cd, Zn, Cu, and Pb). Their results showed the potential of olivine minerals for treating industrial wastewaters laden with heavy metals. The metal RE% of PO was higher at pH of 7 than 5. Figures 2A and 2B shows that the percent removal of all metals improved at pH 7 compared to pH 5 when using PO. When PO and GO are compared, a small discrepancy in metal removal for the two forms of solids was observed. The authors noted that GO removed metals with hard-shell (small, highly charged and non-polarizable) type character (especially Cd) better than PO, whilst PO better removed metals with soft-shell (larger, less charged and polarizable) properties (i.e., Zn, Cu, Pb) compared with GO. However, PO and GO showed comparable metal uptake reactivity for Co and Ni. Furthermore, the RE% for all metals increased as the reaction time increased.

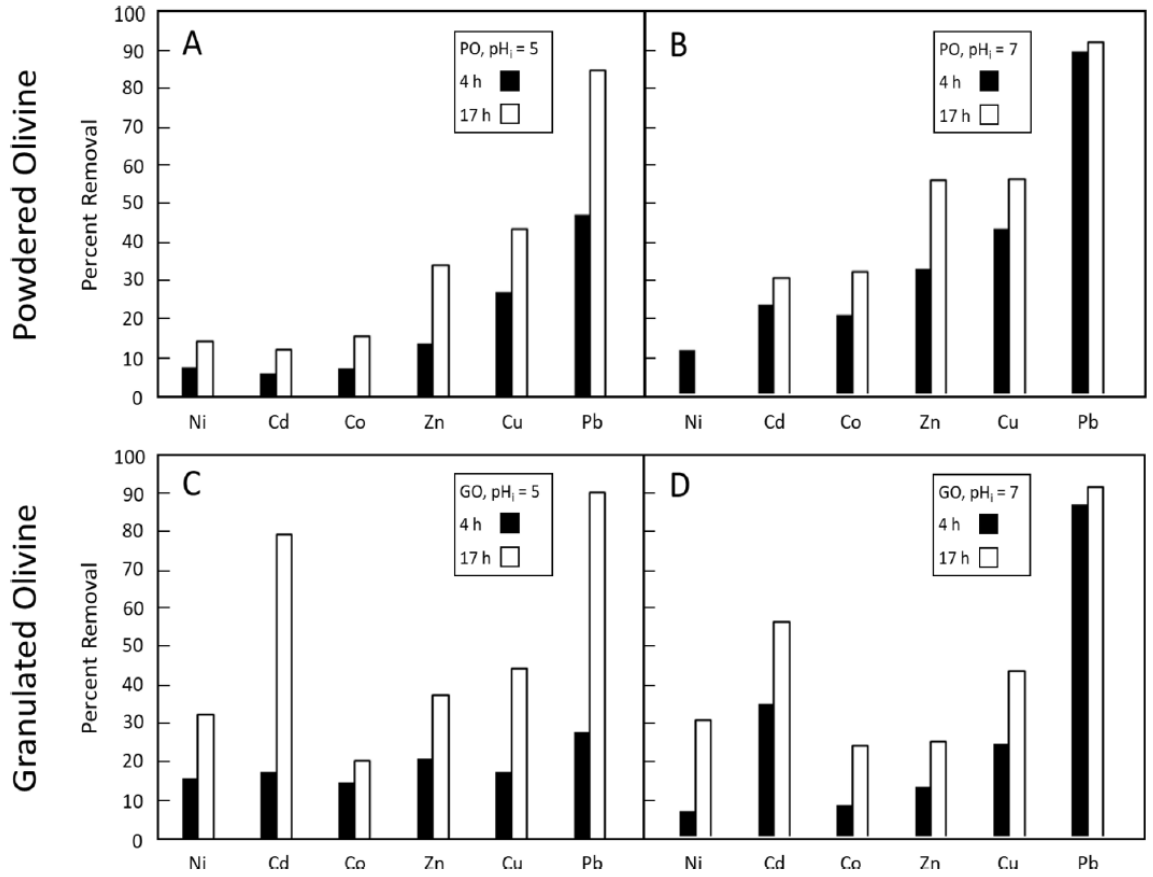

Fig. 2. RE% of the metals (Ni, Cd, Co, Zn, Cu and Pb) at: (A, C) pH of 5, and (B, D) pH of 7, using: (A, B) powdered olivine (0.3 g/L), and (C, D) granulated olivine (0.5 g/L). Adapted from (van Genuchten et al., 2023) with permission.

In addition, in that study the authors provided a more comprehensive analysis of the variations in solution composition during a reaction time of 17 hours for the metals (Pb, Zn, Cd) using PO and GO. When PO was used to remove Pb, Zn and Cd, a substantial increase in pH was recorded and the release of Si (up to 26 μM) was also noticed as indicated in Figure 3. Given the alkalinity of the solutions (~80 mg/L), the authors demonstrated that such alterations in aqueous chemistry caused by olivine dissolution generate thermodynamically more favorable conditions for precipitation of Zn-containing oxides (oxyhydroxides), carbonates and silicates (van Genuchten et al., 2023).

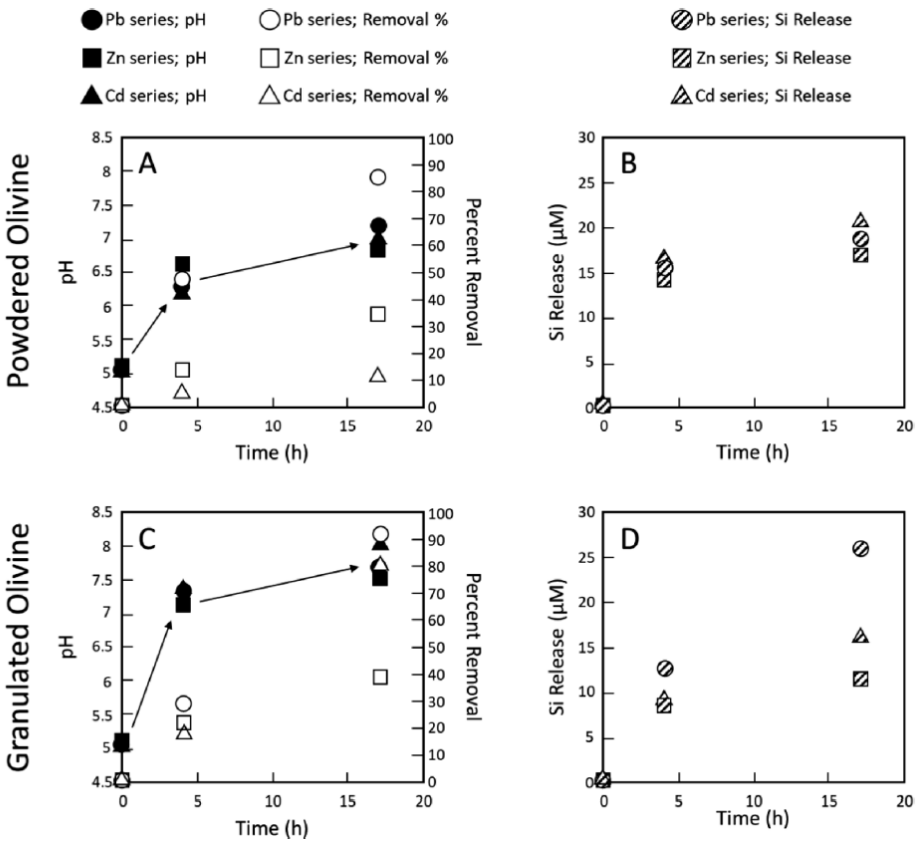

Fig. 3. Changes observed in pH (black symbols), metal RE% (white symbols) and dissolved Si (striped symbols) as a function of time using powdered olivine (PO) or granulated olivine (GO). The circles, squares and triangles show experiments with Pb, Zn and Cd. Adapted from (van Genuchten et al., 2023) with permission.

Another study reported that ions such as Cu^{2+}, Pb^{2+} or Fe^{3+} can be removed efficiently using activated minerals such as serpentine and calcite, while other ions such as Cd^{2+}, Ni^{2+} and Mn^{2+} have a propensity to stay in the solution (Chen et al., 2025). This is because Cd^{2+} is prone to hydrolyze and form complexes with six water molecules, and presents in a stable octahedral form ($Cd(OH_2)_6^{2+}$), limiting its adsorption onto mineral surfaces, in comparison to other heavy metal ions with less water coordination such as Cu^{2+} ($Cu(H_2O)_4^{2+}$ in water. While individual carbonate or silicate minerals are insufficient for effective stabilization of Cd^{2+}, in the presence of other heavy metal ions such as Cu^{2+} and Zn^{2+}, studies have demonstrated the feasibility of boosting Cd removal by formulating minerals with other chemicals or minerals together. Therefore, the authors prepared an efficient adsorbent by simply co-milling olivine with magnesite. During ball-milling, the continuous input of high energy, destroys the crystal structures of olivine and magnesite, and a chaotic active interface and amorphous regions are created between the two surfaces. This allows Mg^{2+} to be easily released, and Cd^{2+} to be precipitated through ion-exchange as $CdCO_3$, even in weak acidic solution. A fixation capacity of Cd^{2+} as high as 270.61 mg/g was achieved, which was much higher than that obtained for the pure minerals and the individual/physical mixture of milled olivine and magnesite. An optimized mass ratio of the two Mg-containing minerals was obtained as in Figure 4. Based on XPS analysis of the co-milled sample before and after Cd^{2+} fixation, it was noted that a new peak appeared following the reaction with Cd, demonstrating the presence of other carbonate which was due to $CdCO_3$ precipitate (Chen et al., 2025).

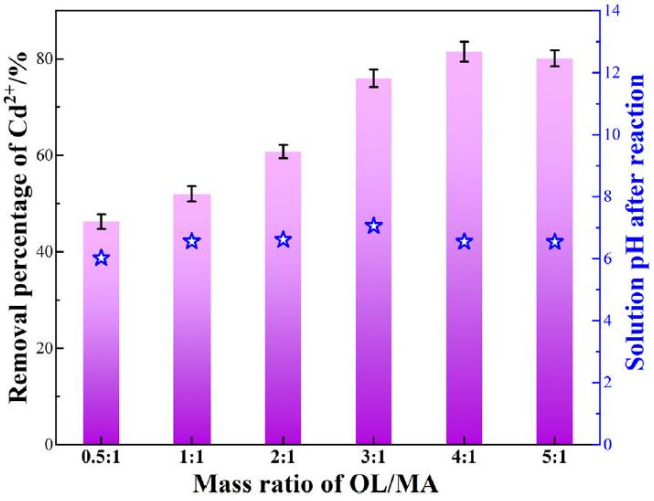

Fig. 4. The impact of various mass ratios of co-milled olivine and magnesite on the RE% percentage of Cd^{2+}. Adapted from (Chen et al., 2025) with permission.

5. Comparative Analysis of the Adsorption Performance of Olivine with Other Materials

One study compared the adsorption performance of four filters in removing Cu, Pb, Ni and Zn from stormwater, which were sand, granulated activated charcoal, pine bark, and granulated olivine (Monrabal-Martinez et al., 2017). The results of that study showed that filters modified with olivine or pine bark performed best both in short and long-run tests. The surface area of the four filters were in the following rank: charcoal > olivine > sand > pine bark. The authors attributed the high removal of the pine bark to compounds such as pectin, lignin, and tannin that carry carboxylic, phenolic, and hydroxyl groups for metals adsorption. However, the authors explained that for fast flow applications such as in areas near road surfaces, high hydraulic conductivity is a significant design parameter to enable a high hydraulic loading, thus adsorbents with bigger particle size are preferred. Whereas in other adsorption applications, the surface area would play a more important role. In another study, (van Genuchten et al., 2023) have compared the removal of Cd, Co, Zn and Cu at pH of 7 using powdered olivine (PO) and powdered calcite (PC). The metal removal was higher with PO than PC in spite of the bigger particle size of PO, as indicated in Figure 5. A notable exception was observed for the behavior of Cd with PC suggesting a unique interplay between Cd and $CaCO_3$. This also explains the enhanced removal observed for Cd with GO (Figure 2) possibly due to the $CaCO_3$ existing in the particle.

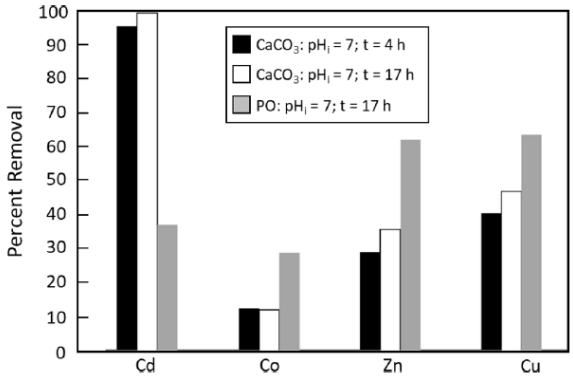

Fig. 5. Compared metal RE% for powdered calcite (PC) (colored in black and white) and powdered olivine (PO) (colored in grey) at a pH of 7. Adapted from (van Genuchten et al., 2023) with permission.

Studies that compare olivine with commonly used adsorbents such as activated carbon are lacking in the literature. Adsorbents such as activated carbon, graphene, and zeolites are characterized by high surface area and therefore high adsorption capacities. However, they are significantly more expensive. Furthermore, olivine is the most plenteous mineral in the Earth's upper mantle (51–60 %) that extends from the bottom of the crust to approximately 410 km (Pamato et al., 2019). Thus, it is a readily available and cost-effective material compared to more expensive raw materials with similar chemical composition. For example, olivine is a cheaper raw material than magnesite in magnesium oxide-based refractory industries. By adopting sustainable and green mining practices and embracing resources circularity, olivine can be considered a potentially durable resource with a low carbon footprint (Luthra et al., 2022).

6. Applications of Olivine in Environmental Remediation

Olivine is an important material used in many applications including metallurgical industries, refractory industries, abrasive grit-blasting materials, raw material for insulating material such as mineral wool and ballast materials and coatings (Sarkar, 2002). Additionally, olivine has been used in applications related to environmental remediation such as carbon sequestration, i.e., converting carbon dioxide from the atmosphere to a stable solid mineral forms (Iozzia et al., 2025, Saleh et al., 2024), water filtration and treatment (Monrabal-Martinez et al., 2017, van Genuchten et al., 2023), soil stabilization and remediation, i.e., improving the strength of soil and/or treating contaminated soil (Emmanuel et al., 2022, Peter and Sayida, 2021, Tahir and Sert, 2023,), and as artificial wetland substrates (Jingpeng et al., 2016). When olivine is added to the soil, it can neutralizes the acidity, stabilize heavy metals, and enhance soil fertility.

7. Future Prospects of Olivine Research in the Field of Water Treatment

Additional studies are required to explore the adsorption mechanisms of olivine for various pollutants including recently emerged pollutants such as nutrients, pharmaceuticals, micro- and nanoplastics. In addition, the long-term stability of olivine adsorbents and their regeneration potential are also lacking. Studies focusing on the tailored modification of olivine to improve its adsorption capacity toward specific pollutants have not also been extensively explored. Studies that investigate the synthesis of olivine composites and the compatibility of olivine with other materials such as activated carbon or biochar can also improve olivine effectiveness. Leaching studies of certain elements from olivine and their impact on the aquatic life would also be important. Finally, scale up studies will be required to investigate the feasibility of olivine adsorbents in real-world applications. If these gaps are addressed, a more comprehensive understanding of the potential of olivine as an effective and sustainable adsorbent in water treatment processes will be gained.

Olivine has recently received significant interest for its potential as an effective adsorbent in water treatment due to its unique properties. However, potential innovations in olivine research would lead to better exploitation of this naturally abundant material for use in this application. For instance, nanostructured olivine can be developed to increase the surface area and reactivity of olivine surfaces, enhancing the kinetics and the capacity of olivine toward various pollutants. In addition, hybrid composites combining olivine with other materials could be fabricated to improve adsorption performance and target a wider range of pollutants. In addition, further research should be directed toward surface functionalization of olivine with polymers and nanoparticles to improve the selectivity of olivine towards specific pollutants. Moreover, integrated processes of adsorption units using olivine with other biological or filtration units can be tested to improve the overall purification performance.

Olivine has played a multifaceted role in addressing emerging environmental challenges due to its exclusive characteristics and promising potential. Therefore, understating the properties of olivine and its dissolution mechanisms could lead to practical solutions to environmental challenges and drive technological innovation. Olivine can contribute to several key areas including sustainable construction materials, energy storage systems, such as batteries and supercapacitors, as well as climate resilience by enhancing the resilience of natural systems to climate impacts such as soil amendment and water treatment.

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