PLANNING MALAYSIA:
Journal of the Malaysian Institute of Planners
VOLUME 22 ISSUE 5 (2024), Page 236 – 247

EVALUATION OF CARBONATED PRODUCT FROM MINERAL CARBONATION OF MINING WASTE FOR CARBON SEQUESTRATION

Umi Rukiah Abdullah[1], Faradiella Mohd Kusin[1,2], Wan Azlina Wan Ab Karim Ghani[3]

[1]Department of Environmental Sciences, Faculty of Forestry and Environment
[2]Institute of Tropical Forestry and Forest Products (INTROP),
[3]Department of Chemical Engineering, Faculty of Engineering,
UNIVERSITI PUTRA MALAYSIA

Abstract

Mining operations generate significant quantities of waste containing alkaline earth silicates, which are valuable for carbon sequestration. Hence, the goal of this study is to assess the possibility of using mining waste to store carbon through a process of mineral carbonation. The study tested mineral carbonation under low reactivity conditions, including ambient pressure and low temperature, to evaluate the effect of pH levels on process efficiency. The samples were discovered to have an alkaline pH, suggesting that they were suitable for mineral carbonation reactions from the beginning. The carbonation process of the mineral was conducted at different pH levels of 8, 10, and 12. The findings showed that the carbonation efficiency was approximately 3%, with the highest level observed at pH 12. Through thermogravimetric analysis, it was observed that there was a multi stage transformation of minerals, which indicated the formation of carbonates containing iron and magnesium. The process captured approximately 33 and 39 g of CO_2/kg. The process indicates that mine waste can be used as a source material for mineral carbonation, as demonstrated by the formation of iron and calcium carbonate products. This research demonstrates that mine waste has the potential for long-term carbon storage, offering a beneficial method for waste management and carbon capture strategies.

Keywords: Mining Waste, Mineral Carbonation; Gold Mine, Carbon Capture and Storage, Waste Management

---

[1] Master Candidate Email: umiabdullah7997@gmail.com

INTRODUCTION

Global greenhouse gas emissions have become a critical environmental issue in recent years. This concern arises from a lack of knowledge and understanding about global greenhouse gas emission, their impacts, and the consequences of global warming. The effects will be in terms of physical changes, climate change, weather patterns, and the resulting economic and environmental changes (Wilson et al., 2009; Muhd-Nor et al., 2016; Mendoza et al., 2019). The examples of greenhouse gases include carbon dioxide (CO_2), methane (CH_4), sulfur oxides (SO_2), ozone (O_3), and nitrous oxide (N_2O). Although carbon dioxide (CO_2) has a lower global warming potential compared to other key greenhouse gases, it is responsible for the majority of emissions due to human activities (Kiptarus 2015; Mohammad-Sabri & Ponrahono 2024) The energy sector is the major contributor to carbon emission globally. The energy sector is the largest global contributor to carbon emissions, with other major contributors including the oil, gas, and mining industries. In particular, the mining industry's reliance on fossil fuels is a major factor in global warming, due to the substantial release of CO_2 emissions with its operations (Jorat et al., 2018). CO_2 emissions in the atmosphere negatively affect the planet's weather and climate systems. The impacts of climate change go beyond just higher average temperatures, also encompassing extreme weather events, changes in wildlife populations and habitats, rising sea levels, and various other factors (Manning et al., 2013; Syed-Hasan et al., 2019)

Mining waste is produced as a result of the extraction and processing of mineral resources (Kivinen, 2017). The mining process generates a large quantity of residues that must be strategically treated and managed to combine economic efficiency with demands for environmental long-term stability (Kusin et al., 2020; Mohd-Isha et al., 2021). Anthropogenic gases, including atmospheric carbon, are the most prevalent gases in the air (Misni et al., 2015). To mitigate CO_2 emissions, carbon sequestration methods can be employed. (Jorat et al., 2020). Mineral carbonation is a carbon sequestration method in which gaseous CO_2 can be captured and turned into stable carbonates (Gerdemann et al., 2003; Azdarpour et al., 2018; Kusin et al., 2019; Rahmani et al., 2020). This will avoid CO_2 from being released back to the atmosphere. According to Olajire (2013) and Ibrahim et al. (2019), utilizing carbon sequestration technology can help capture a large quantity of carbon emissions for extended periods of time. A method called carbon sequestration, or carbon capture and storage (CCS), has been suggested as a way to securely store carbon in a stable form for an extended period of time. The process of mineral carbonation involves using carbon-intensive industrial waste, such as mining waste, as the raw material for the process (Li & Hitch, 2018).

The interaction of basic minerals with CO_2 to produce non-toxic solid carbonate is called mineral carbonation (Omale et al., 2019; Lavikko, 2017). This can happen naturally, but a small change to speed up this natural process could help reduce the amount of additional CO_2 in the atmosphere, thereby reducing global temperatures (Pan et al., 2012; Ohenoja et al., 2020). Equation (1) represents a mineral carbonation reaction, in which CO_2 combines with mineral-containing metal oxides to produce insoluble carbon (Lechat et al., 2016). Magnesium silicate minerals (e.g. Mg_2SiO_4, $Mg_3Si_2O_5(OH)_4$) and silicates rich in Fe or Ca are examples of raw materials for mineral carbonation (e.g. Fe_2SiO_4, $CaSiO_3$). Basically, these minerals can be found in large quantities in many different wastes.

$$\text{Metal oxide} + CO_2 \rightarrow \text{Metal Carbonate} + \text{Heat} \quad (1)$$

Previous research on mineral carbonation for carbon sequestration has mainly relied on the process of carbonation and the potential of different mining waste materials. However, there are still some unresolved issues that require attention. The carbonated products have not been thoroughly characterized in terms of their mineralogical and structural properties, which is crucial for evaluating their long-term stability (Nowak et al., 2013). In addition, there has been a lack of detailed and controlled optimization of process parameters, such as temperature, pressure, and additives, resulting in inconsistent result (O'Connor et al., 2005). Moreover, it is necessary to investigate the implementation of these procedures into current industrial activities in order to improve effectiveness and decrease expenses (Wang & Maroto-Valer, 2011). There is a lack of specific case studies or practical applications in the existing studies, which makes it difficult to demonstrate the real-world practicality of mineral carbonation (Wilson et al., 2009). Apart from that, the potential for carbon sequestration in mine waste has yet to be investigated.

Therefore, this research investigates an innovative application of gold mine waste by utilizing mineral carbonation at varying pH levels for CO_2 sequestration. The primary objectives of this study are to evaluate the potential of mining waste for capturing and storing carbon dioxide by mineral carbonation, as well as to determine the effect of varying pH on mineral carbonation process under ambient CO_2 pressure and temperature (Olajire, 2013). This will provide an insight into the management and utilization of waste material in tackling the global carbon emission issue from the perspective of a technological application.

MATERIALS AND METHODS

Materials Preparation

Gold mining waste was collected from a gold mine in the state of Pahang, Malaysia. Collected samples consist of mine tailing samples in the form of sediment and sludge. As sample analysis and mineral carbonation experiment requires samples of size smaller than 1mm, the sediment samples were pre-treated to prepare for uniform-sized particles. The materials were dried for 24 hours at room temperature, grounded into fine particles, and homogenized with a <63 µm sieve. The pH of the gold mine waste was tested using British Standard (BS) 1377, to ascertain its natural pH.

pH Analysis

A soil testing method developed from British Standard (BS) 1377 was used to evaluate the pH of the samples (Syed Hasan et al., 2018). 30 g of raw sample and 75 ml of distilled water were combined in a 1: 2.5 ratio, with 30 g of raw sample and 75 ml of distilled water used. The pH of the liquids was then tested using a pH meter after 24 hours.

Mineral Carbonation Experiment

Carbonation experiment was conducted using a customized 250 ml closed stainless steel reactor. For this experiment, the manipulated variables were pH (as shown in Table 1) while constant variables were particle size (63 µm) and temperature (80°C). The pH of the sample mixture was measured using a pH meter as the manipulated variable. For each sample, three levels of pH were used, which are pH 8, 10, and 12. A 1M NaOH solution was added to the solution to raise the pH of the sample. 50 ml of 1 M sodium chloride (NaCl) and 50 ml of 0.64 M sodium bicarbonate ($NaHCO_3$) solution were mixed with the samples and put into the Teflon cup. To alter the pH to the appropriate value, 1 M sodium hydroxide (NaOH) or 1 M hydrochloric acid (HCl) was added to the solution in the experiment (Azdarpour et al., 2018). In mineral carbonation experiments, the use of various additives and solvents has been examined to improve Ca, Mg, and Fe solubility (Muwanguzi et al., 2012). The experimental set-up is shown in Figure 1, while the working parameters and constant parameters are summarized in Table 1.

To change the pH to the appropriate value, 1 M sodium hydroxide (NaOH) or 1 M hydrochloric acid (HCl) was added to the solution in the experiment (Azdarpour et al., 2018). In mineral carbonate experiments, the use of different additives and solvents was examined to improve the solubility of Ca, Mg and Fe (Muwanguzi et al., 2012). The experimental setup is shown in Figure 1, while the working parameters and constants are summarized in Table 1.

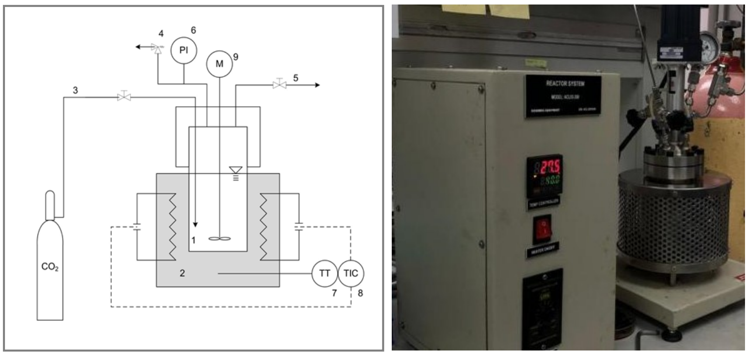


Figure 1: Mineral carbonation experimental set-up as shown in (a) schematic diagram and (b) actual stainless-steel reactor used.

Table 1: Parameters used in mineral carbonation experiment

Adjusted Parameter	pH 8,10,12
Constant Variables	Particle size = 63 µm, Temperature = 80°C CO_2 pressure = 1 bar Reaction time = 1 hour Stirring speed = 300 rpm Solution = 1 M NaCl & 0.64 M $NaHCO_3$

The Teflon cup filled with the mixture was placed into the carbonation reactor, sealed airtight, and heated to a constant temperature of 80°C. The solution was swirled continuously at 300 rpm while 1 bar of CO_2 pressure was introduced. For each experiment, the reaction was allowed to run for around an hour. The carbonation product was filtered and dried at 105°C overnight before being evaluated using a thermogravimetric analyzer (TGA).

Thermogravimetric Analysis

Thermogravimetric analysis (TGA) was carried out to determine the carbonate conversion rate of the mining waste samples (Goldstein, 2003). TGA was used to measure the weight loss of a sample as it is heated continuously from room temperature 25°C to 1200°C. TGA was chosen because it is a reliable method for determining carbonate concentration in solids and is applicable to a wide range of industries. The procedure of this analysis was to expose the samples to high temperatures ranging from 0 to 950 degrees Celsius and the formation of carbonates were observed at certain temperature range. Equations (2) to (4) below were used to compute the carbonation efficiency.

$$\text{Purity } FeCO_3/MgCO_3 = \%\, weight\ loss\ x\ \frac{Molecular\ weight\ of Fe/Mg}{Molecular\ weight\ of\ CO_2} \qquad (2)$$

Fe/Mg mass in $FeCO_3/MgCO_3$ (3)

$$= \%\, weight\ loss\ x\ \frac{molecular\ weight\ of Fe/Mg}{Molecular\ weight\ of\ CO_2}\ x\ mass\ of\ solid\ residue$$

$$\text{Carbonation efficiency (\%)} = \frac{Fe/Mg\ mass\ in\ FeCO_3/MgCO_3}{Fe/Ca\ total\ mass\ in\ feeding\ material} \times 100 \qquad (4)$$

RESULTS AND DISCUSSION

Characterization of Mining Waste

The mineralogical composition of gold mining waste consists of silicate minerals such as quartz, graphite, muscovite, kaolinite, chlorite, chlorite-serpentine, illite, aerinite, stilpnomelane and sepiolite. Specifically, illite and chlorite-serpentine are the major minerals present in the sludge and sediment of the gold mining waste, with minor amount of quartz (Figure 2). These minerals are typically produced from the chemical weathering of alumino-silicates existing under tropical environment.

Consistent with mineralogical analysis, the chemical composition of the gold mine waste was determined as having iron oxide, Fe_2O_3 of about 3-12% wt. and magnesium oxide, MgO of 2-6% wt. Other oxide elements include SiO_2, Al_2O_3, K_2O and SO_3. The Al_2O_3 compound was associated with kaolinite, while K_2O originated from illite minerals. These alumino-silicate minerals have a high affinity for CO_2, which can be utilized in a process where CO_2 is converted into stable carbonates. The presence of iron oxide (Fe_2O_3) and magnesium oxide (MgO) further supports this, as both iron and magnesium carbonates can form stable, long-term carbon sequestration compounds.

The microstructure of the mine waste sample was evidenced by the hexagonal shape crystals as observed in the SEM micrographs (Figure 3). This is believed to be associated with minerals kaolinite (Figure 3a) and presence of chlorite-serpentine (Figure 3b) in the mine tailings which was depicted by their tabular shape as seen in the SEM micrographs.

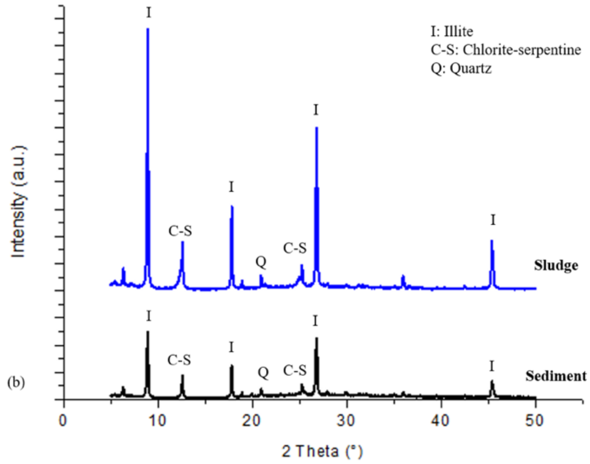
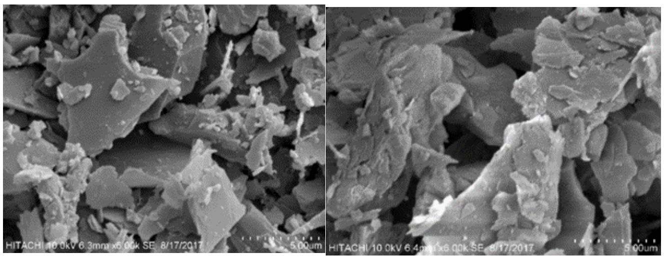


Figure 2: X-ray diffractograms of sludge and sediment from gold mine tailings.



(b)

Figure 3: Microstructure images of mining waste sample for mineral carbonation

Overall, characterizing gold mining waste is necessary in order for it to be used as a feedstock for mineral carbonation and to improve carbonation efficiency in sequestering CO_2.

Carbonation Efficiency as a Function of pH

The Fe/Mg carbonation efficiency of the gold mine waste as influenced by pH are given in Table 2. An increase in pH from 8 to 12 resulted in higher Fe/Mg carbonation efficiency, with values ranging from 2.19% - 2.78% for Fe and 1.86% - 2.41% for Mg. From TGA analysis, the carbonation efficiency corresponds to the $FeCO_3$ purity (12.15-14.43%) and $MgCO_3$ purity (8.73-10.06%), respectively. The corresponding TGA mass loss owing to Fe carbonate decomposition was 5.11-6.22%, and the TGA mass loss due to Mg carbonate decomposition was 3.84-4.43%. From the results, a higher Fe/Mg carbonation efficiency can be seen as pH increases from 8 to 12, indicating that pH plays important role in the mineral carbonation process. The mining waste Fe/Mg carbonation efficiencies are seen to be influenced by the varied pH employed in the mineral carbonation process where a higher pH, i.e. pH 12 might increase the process efficiency (Syed-Hassan et al., 2018).

The Fe/Mg carbonation conversion efficiency was enhanced as pH were raised to a more alkaline state from 8 to 12. Clearly, pH is an important factor in the conversion of Fe and Mg to carbonates, with a higher pH of 12 achieving a higher carbonation efficiency. This was also reflected by the purity of the carbonate products. It can be seen that the $FeCO_3$ purity and $MgCO_3$ purity of the samples correspond with the trend of the increasing pH. Thus, a greater efficiency process might produce a carbonate product with a higher purity.

Therefore, the presence of potential divalent cations in the mining waste, such as in this case Fe and Mg may aid in the sequestration of CO_2 into carbonate form by mineral carbonation process in this case. The process preferably occurs with a higher alkaline pH, thus enhancing the Fe/Mg carbonation efficiency. However, this process takes place at an ambient CO_2 pressure and at a low reaction temperature of 80°C.

Table 2: Average Fe and Mg carbonation efficiency of mine waste as influenced by pH.

Parameter	Operating variable	Average Fe carbonation efficiency, %	Average Mg carbonation efficiency, %	Average $FeCO_3$ purity, %	Average $MgCO_3$ purity, %	Mass loss in TGA[a], %	Mass loss in TGA[b], %
pH	8	2.19	1.86	12.15	8.73	5.11	3.84
	10	2.44	2.39	12.59	9.61	5.43	4.23
	12	2.78	2.41	14.43	10.06	6.22	4.43

[a] Average mass loss related to Fe carbonate decomposition
[b] Average mass loss related to Mg carbonate decomposition

It has been examined that mineralization of Fe and Mg carbonate depends on the pH, where the increase of pH favors for the increasing carbonation efficiency. A higher Fe and Mg carbonation efficiency was achieved when mining waste with pH 12 was used in the carbonation experiment. Generally, a higher carbonation efficiency was observed at pH 12 under the low operating conditions (ambient pressure-temperature).

Sequestered CO_2 in Carbonated Product

The TGA mass loss due to carbonate breakdown, which releases carbon dioxide, used to calculate the amount of carbonates ($FeCO_3$ and $MgCO_3$) produced, and the amount of CO_2 sequestered (Hitch et al., 2009). Based on the product mass loss from the TGA analysis and the following reactions, the stoichiometric CO_2 sequestration uptake was calculated.

TGA analysis assuming the following reactions:

$$CaCO_3 \rightarrow CO_2 + CaO \quad (5)$$

$$FeCO_3 \rightarrow CO_2 + FeO \quad (6)$$

$$MgCO_3 \rightarrow CO_2 + MgO \quad (7)$$

Overall, the production of $FeCO_3$ and $MgCO_3$ in the final carbonation products are given in Table 3. This is based on the chemical reactions between Mg-Fe-silicate minerals in the mine waste samples with the presence of CO_2, which is capable of sequestering CO_2 in the form of carbonate in stable form.

Table 3: Carbonated product from mine waste utilization in mineral carbonation (amount of $FeCO_3$ and $MgCO_3$ formed and sequestered CO_2).

Parameter	Operating variable	$FeCO_3$, g/kg sample	$MgCO_3$, g/kg sample	% $FeCO_3$	% $MgCO_3$
pH	8	154.39	57.76	72.77	27.23
	10	151.42	51.34	74.68	25.32
	12	162.76	65.45	71.32	28.68
	Operating variable	$^aCO_2$ uptake, g/kg sample	$^bCO_2$ uptake, g/kg sample	Total CO_2 uptake, g/kg sample	Theoretical CO_2 uptake, g/kg sample
pH	8	30.34	3.66	34.00	212.15
	10	30.14	2.99	33.13	202.76
	12	34.65	4.83	39.48	228.21

^{a}CO_2 uptake from $FeCO_3$ conversion
^{b}CO_2 uptake from $MgCO_3$ conversion

It can be seen that the amount of $FeCO_3$ sequestered are in the range of 151.42-162.76 g/kg mine waste. While the sequestered $MgCO_3$ ranges from 51.34-65.45 g/kg mine waste. The composition of the final carbonated products was composed of around 71-74% $FeCO_3$ and 25-28% $MgCO_3$, with other minerals also present. In terms of the CO_2 sequestration uptake, it can be observed that varying the pH from 8-12 resulted in 30-34 g CO_2 uptake/kg sample from $FeCO_3$ conversion. While about 3-4.8 g CO_2 /kg sample was captured from the conversion of $MgCO_3$. The amount captured follows the theoretical CO_2 uptake from stoichiometric conversion, although in much lower amount. This can be anticipated when using waste material for carbonate conversion as opposed to using natural minerals.

CONCLUSION

This study demonstrates the potential of utilizing mining waste as a valuable resource for mineral carbonation, which could be an effective method for capturing carbon dioxide from the air. The waste samples need to contain minerals such as iron and magnesium in order to improve the carbonation process. According to researchers, using particles smaller than 63μm and adjusting pH levels between 8 to 12 greatly enhanced carbonation efficiency. Furthermore, the study shows that carbonation efficiency increases with higher pH levels, emphasizing the importance of pH control in optimizing CO_2 efficiency. This study demonstrated a CO_2 capture potential ranging from 33 to 39 g CO_2/kg of mine waste, predominantly through the formation of $FeCO_3$ and $MgCO_3$ compounds during mineral carbonation processes. These findings shown the potential of mine waste as a valuable feedstock for carbon sequestration via mineral carbonation under varying conditions. Therefore, it is recommended that future research focus on optimizing the carbonation process to improve the efficiency of CO_2 sequestration. Furthermore, research should explore practical applications and opportunities for utilizing mining waste as a sustainable solution for reducing greenhouse gas emissions.

ACKNOWLEDGMENTS

This research was funded by the Ministry of Higher Education Malaysia, grant number FRGS/1/2023/TK08/UPM/02/9 (FRGS 5540604) and Universiti Putra Malaysia, grant number IPS 9709500.

REFERENCES

Azdarpour, A., Karaei, M. A., Hamidi, H., Mohammadian, E., & Honarvar, B. (2018). CO_2 sequestration through direct aqueous mineral carbonation of red gypsum. *Petroleum*, 4(4), 398-407. https://doi.org/10.1016/j.petlm.2017.10.002

Gerdemann, S. J., Dahlin, D. C., & O'Connor, W. K. (2002). Carbon dioxide sequestration by aqueous mineral carbonation of magnesium silicate minerals. In *Greenhouse Gas Control Technologies – 6th International Conference* (Vol. 1, pp. 677-682). https://doi.org/10.1016/B978-008044276-1/50108-2

Goldstein, J., Newbury, D. E., Joy, D. C., Layman, C. E., Echlin, P., Lifshin, E., Sawyer, L., & Micheal, J. R. (2003). *Scanning electron microscopy and X-ray microanalysis* (3rd ed.). *Kluwer Academic/Plenum Publisher*.

Hitch, M., Ballantyne, S. M., & Sarah, R. (2009). Revaluing mine waste rock for carbon capture and storage. *International Journal of Mining, Reclamation and Environment*, 24(1), 64-79. https://doi.org/10.1080/17480930902843102

Ibrahim, M. H., El-Naas, M. H., Benamor, A., Al-Sobhi, S. S., & Zhang, Z. (2019). Carbon mineralization by reaction with steel-making waste: A review. *Processes*, 7, 115.

Jorat, M. E., Goddard, M. A., Manning, P., Lau, H. K., Ngeow, S., Sohi, S. P., & Manning, D. A. C. (2020). Passive CO_2 removal in urban soils: Evidence from brownfield sites. *Science of the Total Environment*, 703, 135573.

Kawigraha, A., Soedarsono, J. W., Harjanto, S., & Pramusanto. (2013). Thermogravimetric analysis of the reduction of iron ore with hydroxyl content. *Advanced Materials Research*, 774–776(July), 682–686.

Kiew, R., & Rahman, R. A. (2021). Plant diversity assessment of karst limestone: A case study of Malaysia's Batu Caves. *Nature Conservation, 44*, 21-49. https://doi.org/10.3897/natureconservation.44.60175

Kiptarus, J. J., Muumbo, A. M., Makokha, A. B., & Kimutai, S. K. (2015). Characterization of selected mineral ores in the eastern zone of Kenya: Case study of Mwingi North Constituency in Kitui County. *International Journal of Mining Engineering and Mineral Processing, 4(1)*, 8–17.

Kivinen, S. (2017). Sustainable post-mining land use: Are closed metal mines abandoned or re-used space? *Sustainability, 9,* 1705.

Kusin, F. M., Che-Awang, N. H., Syed-Hasan, S. N. M., Abdul-Rahim, H. A., Azmin, N., Jusop, S., & Kyoung-Woong, K. (2019). Geo-ecological evaluation of mineral, major and trace elemental composition in waste rocks, soils, and sediments of a gold mining area and potential associated risks. *Catena*, *183*, 104229.

Kusin, F. M., Syed-Hasan, S. N. M., Hassim, M. A., & Molahid, V. L. M. (2020). Mineral carbonation of sedimentary mine waste for carbon sequestration and potential reutilization as cementitious material. *Environmental Science and Pollution Research*, *27(11)*, 12767–12780.

Lackner, K. S., Wendt, C. H., Butt, D. P., Joyce, E. L., & Sharps, D. H. (1995). Carbon dioxide disposal in carbonate minerals. *Energy, 20*, 1153–1170.

Lavikko, S. (2017). Geological and mineralogical aspects on mineral carbonation (Ph.D. thesis). *Åbo Akademi University*.

Lechat, K., Jean-Michel, L., Molson, J., Beaudoin, G., & Hébert, R. (2016). Field evidence of CO_2 sequestration by mineral carbonation in ultramafic milling wastes, Thetford Mines, Canada. I*nternational Journal of Greenhouse Gas Control*, *47*, 110–121.

Manning, D. A. C., Renforth, P., Lopez-Capel, E., Robertson, S., & Ghazireh, N. (2013). Carbonate precipitation in artificial soils produced from basaltic quarry fines and composts: An opportunity for passive carbon sequestration. *International Journal of Greenhouse Gas Control*, *17*, 309–317.

Mendoza, E. Y. M., Santos, A. S., López, E. V., Drozd, V., Durygin, A., Chen, J., & Saxena, S. K. (2019). Iron oxides as efficient sorbents for CO_2 capture. *Journal of Materials Research and Technology*, *8(3)*, 2944–2956.

Misni, A., Jamaluddin, S., & Kamaruddin, S. M. (2015). Carbon sequestration through urban green reserve and open space. *Planning Malaysia*, *13(5)*.

Mohammad-Sabri, S. A., & Ponrahono, Z. (2024). Greening the city: Criteria and indicators for evaluating the effectiveness of small urban parks in promoting urban resilience to climate change. *Planning Malaysia*, *22(30)*.

Mohd-Isha, N. S., Kusin, F. M., Kamal, N. M. A., Hasan, S. N. M. S., & Molahid, V. L. M. (2021). Geochemical and mineralogical assessment of sedimentary limestone mine waste and potential for mineral carbonation. *Environmental Geochemistry and Health*. https://doi.org/10.1007/s10653-020-00784-z

Muhd-Nor, N. H., Selamat, S. N., Rashid, M. H. A., Ahmad, M. F., Jamian, S., Kiong, S. C., Hassan, M. F., Mohamad, F., & Yokoyama, S. (2016). Carbon sequestration and carbon capture and storage (CCS) in *Southeast Asia. Journal of Physics: Conference Series*, *725*, 012010.

Muwanguzi, A. J. B., Karasev, A. V., Byaruhanga, J. K., & Jonsson, P. G. (2012). Characterization of chemical composition and microstructure of natural iron ore from Muko deposits. *International Scholarly Research Network ISRN Materials Science*, 1–9.

Nowak, D. J., Greenfield, E. J., Hoehn, R. E., & Lapoint, E. (2013). Carbon storage and sequestration by trees in urban and community areas of the United States. *Environmental Pollution, 178,* 229-236. https://doi.org/10.1016/j.envpol.2013.03.019

O'Connor, W. K., Dahlin, D. C., Rush, G. E., Gerdemann, S. J., Penner, L. R., & Nilsen, D. N. (2005). Aqueous mineral carbonation. *Mineral Processing and Extractive Metallurgy Review, 26(5)*, 227-246.

Ohenoja, K., Rissanen, J., Kinnunen, P., & Illikainen, M. (2020). Direct carbonation of peat-wood fly ash for carbon capture and utilization in construction application. *Journal of CO_2 Utilization*, *40*, 101203.

Olajire, A. A. (2013). A review of mineral carbonation technology in sequestration of CO_2. *Journal of Petroleum Science and Engineering, 109*, 364–392. https://doi.org/10.1016/j.petrol.2013.03.013

Omale, S. O., Choong, T. S. Y., Abdullah, L. C., Siajam, S. I., & Yip, M. W. (2019). Utilization of Malaysia EAF slags for effective application in direct aqueous sequestration of carbon dioxide under ambient temperature. *Heliyon*, *5*, e02602.

Pan, S.-Y., Chang, E. E., & Chiang, P.-C. (2012). CO_2 capture by accelerated carbonation of alkaline wastes: A review on its principles and applications. *Aerosol and Air Quality Research*, 1, 770–791.

Rahmani, O. (2020). An experimental study of accelerated mineral carbonation of industrial waste red gypsum for CO_2 sequestration. *Journal of CO_2 Utilization*, *35*, 265-271.

Syed-Hasan, S. N. M., Mohd Kusin, F., Jusop, S., & Mohamat Yusuff, F. (2019). The mineralogy and chemical properties of sedimentary waste rocks with carbon sequestration potential at the Selinsing gold mine, Pahang. *Pertanika Journal of Science & Technology*, *27(2)*, 1005-1012.

Wang, X., & Maroto-Valer, M. M. (2011). Dissolution of serpentine using recyclable ammonium salts for CO2 mineral carbonation. *Fuel, 90(3)*, 1229-1237. https://doi.org/10.1016/j.fuel.2010.10.040

Wilson, S. A., Dipple, G. M., Power, I. M., Thom, J. M., Anderson, R. G., Raudsepp, M., Gabite, J. E., & Southam, G. (2009). Carbon dioxide fixation within mine wastes of ultramafic-hosted ore deposits: Examples from the Clinton Creek and Cassiar chrysotile deposits, Canada. *Economic Geology, 104*, 95–112.

Received: 19th March 2024. Accepted: 3rd September 2024