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Sequestering Atmospheric CO_2 Inorganically: A Solution for Malaysia's CO_2 Emission

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Abstract: Malaysia is anticipating an increase of 68.86% in CO_2 emission in 2020, compared with the 2000 baseline, reaching 285.73 million tonnes. A major contributor to Malaysia's CO_2 emissions is coal-fired electricity power plants, responsible for 43.4% of the overall emissions. Malaysia's forest soil offers organic sequestration of 15 tonnes of CO_2 $ha^{-1}\cdot year^{-1}$. Unlike organic CO_2 sequestration in soil, inorganic sequestration of CO_2 through mineral carbonation, once formed, is considered as a permanent sink. Inorganic CO_2 sequestration in Malaysia has not been extensively studied, and the country's potential for using the technique for atmospheric CO_2 removal is undefined. In addition, Malaysia produces a significant amount of solid waste annually and, of that, demolition concrete waste, basalt quarry fine, and fly and bottom ashes are calcium-rich materials suitable for inorganic CO_2 sequestration. This project introduces a potential solution for sequestering atmospheric CO_2 inorganically for Malaysia. If lands associated to future developments in Malaysia are designed for inorganic CO_2 sequestration using demolition concrete waste, basalt quarry fine, and fly and bottom ashes, 597,465 tonnes of CO_2 can be captured annually adding a potential annual economic benefit of €4,700,000.

Keywords: CO_2 emission; Malaysia; inorganic CO_2 sequestration; demolition concrete waste; basalt quarry fine; fly and bottom ash

1. Introduction

According to the International Energy Agency [1], the world's annual carbon dioxide (CO_2) emissions grew from 17.78 billion tonnes in 1980, to 32.10 billion tonnes in 2015. Stern [2] reported that, if no action is taken to reduce greenhouse gas (GHG) emissions, the concentration of GHGs in the atmosphere would become double its preindustrial level by as early as 2035. According to the Institute of Energy Economics, Japan (IEEJ) 2018 Outlook—Prospects and Challenges until 2050 [3], the global energy demand continues to increase from 1990 to 2050. Based on this predicted energy outlook, two thirds of the energy growth comes from non-Organisation for Economic Co-operation and

Development (OECD) Asia, including China, India, Association of Southeast Asian Nations (ASEAN) countries, and others in Asia, Middle East, North Africa, sub-Saharan Africa, Europe, and Latin America. Three quarters of the energy growth until 2050 will be utilised for fueling power generation and transportation. Coal, natural gas, and biomass are the three main sources for electricity production. The International Energy Agency [4] indicated that the electricity produced using fossil fuels is responsible for nearly 40% of the world's overall energy-related CO_2 emissions. CO_2 emissions related to the main carbon emitting industries such as iron and steel industry, cement industry, petroleum refining, and the pulp and paper industry accounts for 30% of the total global anthropogenic emission of CO_2, responsible for a significant portion of industry-related CO_2 emissions [5]. However, emissions related to power generation still stand as the main contributor to industry-related CO_2 emissions. According to the statistical data from Global Report on Human Settlement, Source on the Cities and climate change, about 75% of CO_2 increment in atmosphere originates from industrial power plants, especially from the burning of fossil fuels [6].

Malaysia is anticipating an increase of 69% in CO_2 emissions in 2020, compared with 2000 baseline, reaching 285.7 million tonnes [7]. Considering Malaysia's population, the per capita GHG emission is 5.9 million tonnes which is three times higher than the levels anticipated for the whole Southeast Asia region [8]. The major contribution to the country's CO_2 emissions is from coal-fired electricity power plants, which are responsible for 43.4% of the overall emissions. The total coal consumption for electricity generation in Malaysia is projected to increase from 12.4 million tonnes in 2005 to 36 million tonnes in 2020 [9].

In 2016 Earth Day, 174 countries singed the 2015 United Nations Climate Change Conference (COP21) Agreement to limit the global warming to 2 °C based on the pre-industrial level. Malaysia is one of the 197 countries that signed the Agreement for active participation in mitigating the carbon emissions by 2030 [10]. The Paris Agreement has acknowledged the requirement to (i) reduce CO_2 emissions and (ii) remove existing CO_2 from atmosphere. Carbon capture and storage (CCS) had been acknowledged as a process of removing CO_2 at high concentration for the long-term duration. This strategy has high potential in mitigating 7 to 70% of cumulative mitigation effort globally by 2100 [11].

Malaysia is committed to the COP21 Paris Agreement. The major reduction in CO_2 emission is likely to be accomplished through the improved efficiency in the energy systems (e.g., low carbon energy and fuels), but the implementation of CCS development programmes would make a significant contribution) to meet the agreement's objectives. Malaysia is one of the Southeast Asia countries investing on minimising concentration of greenhouse gases (GHGs) in general and CO_2 through defined strategies falling under CCS development [12].

CO_2 removal in geological and terrestrial reservoirs through anthropogenic activities are recommended as a method to fight global warming [13]. Mineral carbonation and using soil as a sink for carbon has been proven as an effective CCS method for permanent atmospheric CO_2 removal [14–21].

In this paper, we review and focus Malaysia's capacity for using soil mineral carbonation (inorganic CO_2 sequestration) as a tool to mitigate the country's high annual CO_2 emissions, and speculate on how far the technique could contribute to the country's commitment to the COP21 Agreement.

2. Malaysia's Position in CO_2 Emissions and CCS

According to a report submitted to the United Nations Framework Convention on Climate Change (UNFCCC) [22], major sources of CO_2 in Malaysia are from:

i. Energy industries: Coal and electrical power industries are the major sources of GHGs emission in Malaysia as well as rest of the world. The total coal consumption for electricity generation in Malaysia is projected to increase from 12.4 million tonnes in 2005 to 36 million tonnes in 2020 [9]. Electricity generation, which contributes 43.40% of total emissions, was discovered to be the largest emitting sector among all sectors.

ii. Transportation sector: This is ranked the second largest GHG emitter among ASEAN countries [23]. This is due to the expansion of conurbation areas such as Kuala Lumpur, where the population is estimated to reach 10 million by 2020 [24]. As a result, motorisation in Malaysia increased five-fold over the past three decades, and proliferation of automobiles is a key contributor towards emission of GHGs [25].

iii. Manufacturing and construction industries: These sectors come in as third for production of GHGs. Malaysia is one of the major manufacturing hubs in ASEAN countries, and remarkable development in this sector is accompanied by high atmospheric CO_2 concentrations [26]. Generally, there are four sources of GHGs emission in manufacturing and construction sectors: (i) Manufacture and transportation of building materials, (ii) Energy consumption of construction equipment, (iii) Energy consumption of processing resources and (iv) Disposal of construction wastes [27]. Figure 1 shows the different sectors for CO_2 emission in Malaysia [22].

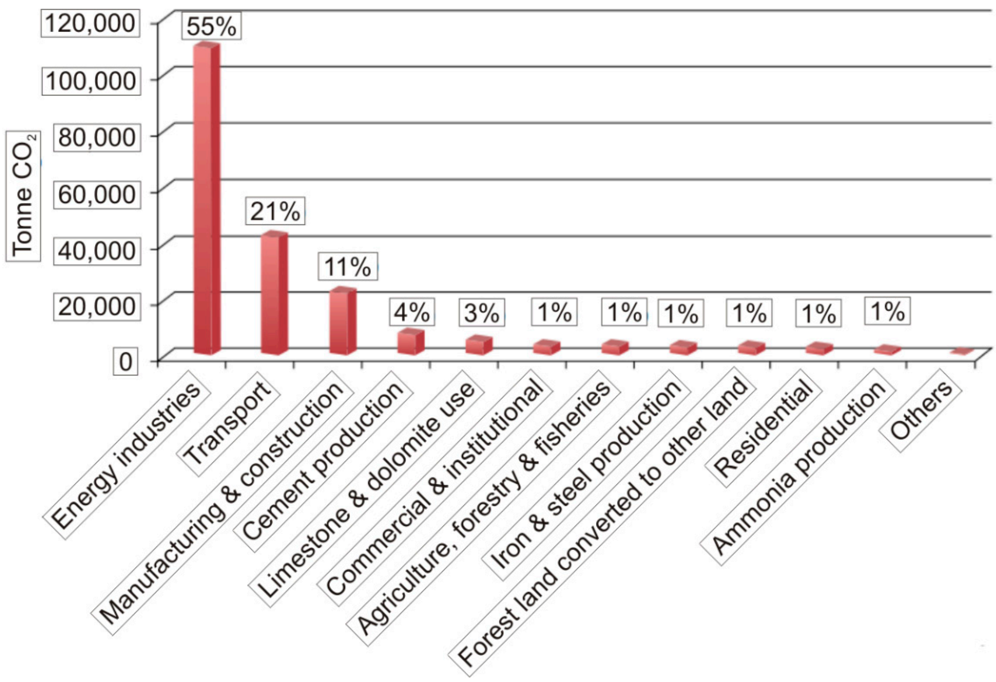

Figure 1. Sectors contributing to CO_2 emissions in Malaysia [22].

According to Malaysia's Intended Nationally Determined Contribution (INDC) [28], by 2030, the country is required to reduce the carbon level to 45% relative to the emissions intensity in 2005. The Malaysian government is persistent in utilising the low carbon industry sector and strengthening the use of green technology through the Government Green Procurement (GGPA) programme. Through the initiatives, the Green Technology Financing Scheme (GTFS) was introduced in 2009, with RM1.5 billion funding to support industries in Malaysia to adopt green technologies. Following the implementation of GTFS scheme in Malaysia, greenhouse gas emission results in 2013 showed a reduction of 94,810 tonnes CO_2 through the applications of green technology. Following the success of the first phase, the second phase was introduced, with allocation of RM5 billion to support industries between 2018 and 2022. Since the power generation sector is the main contributor to the country's overall CO_2 emissions, the Malaysian government's focus is to mitigate excessive emissions generated by this sector. To address this, in 2008 the Malaysian government established Efficient Management of Electrical Energy Regulation (EMEER) to reduce electricity consumption in Malaysia [10].

Malaysia is setting up sustainable regulations aligned with the moving forward strategy 'Transformasi Nasional 2050', known as TN50. The main objective of TN50 is to ensure achievements of the country's Vision 2020 goals, which is to place Malaysia as the top 20 biggest economies in the world, as a model state for management issues related to climate change, and provide affordable and clean energy by 2050. In addition, Malaysia, as an ASEAN country, has adopted the ASEAN Plan of Action for Energy Cooperation (APAEC), and is targeting to reduce the ASEAN energy intensity by 20% in 2020 and 30% by 2050 [10].

Efforts have been made to implement CCS techniques in Malaysia, in line with the TN50 objectives to mitigate impacts of country's CO_2 emissions. The majority of the works towards CCS have been limited to small-scale research projects, however, two existing commercial-scale CCS-related projects in Malaysia are summarised below:

i. K5 Strategic Technology Project: Malaysia is known as the second-biggest oil producer in Southeast Asia, and the country's national oil company, Petronas, is taking part in CCS development to revive the K5 sour gas project in shallow waters off Sarawak through deployment of carbon capture technologies. The K5 project began in 1970, and contains a gas reservoir of approximately 21 trillion cubic feet. The K5 project gas processing is associated with high CO_2 emissions and, therefore, Petronas has introduced 'K5 Strategic Technology Project' as a pilot scheme to tackle the issues associated with the reservoir's CO_2 emission using CCS technologies. The company is aiming to manufacture and install the first-ever specially built CO_2 processing platform in Malaysia by 2022. The platform will have a hull weighing 11,000 tonnes, and the upper part of offshore, topsides of 9000 tonnes with the attached facilities, are designed to capture CO_2 and transport it into the same offshore reservoir below the seabed [29]. The topside of the platform literally consists of the oil production plant, accommodation board, and drilling rig [29].

ii. TNB Janamanjung Project: One of the initiatives by Malaysia is application of CCS in coal-fired power stations at TNB Janamanjung, built on a man-made island located in Seri Manjung, Perak. By using post-combustion CCS technology, approximately 85%–95% (8.5–9.5 million tonne CO_2 year^{-1}) of the CO_2 is captured and compressed from the processed plant. Later, the compressed CO_2 is transported using an alternative line along the PETRONAS Peninsular Gas Utilization (PGU) project to transfer the captured CO_2 offshore in Terengganu [30]. It is estimated that the PGU system extends to over 1700 km, and the compressed CO_2 can be transferred to the west coast of Peninsular Malaysia where oil and gas exploration is being conducted for geological storage, especially for enhanced oil recovery (EOR).

There is no doubt that CCS technology provides abundant opportunities for CO_2 removal. However, several challenges need to be identified for continuous use of the technique in large and commercial scale. The first and most important challenge is the cost associated with CCS. It is estimated that the overall costs for CCS are within US$30–70 per tonne CO_2, with the separation and compression processes accounting for over 75% of overall CCS project costs, whereby underground storage accounts for US$3–10 per tonne CO_2 [31,32]. Accordingly, to implement the CCS technique at a national level, a significant financial contribution needs to be secured by the Malaysian government. Provision of transportation facilities and infrastructures required for transportation of CO_2 to storage sites are hurdles that have an impact on effectiveness of this technique. The choices of transportation depend on the distance between field and storage sites, available infrastructure, available cost, and geography or geology of the route. Therefore, technical aspects must be considered when contemplating the CCS projects in Malaysia. In terms of storage sites, reservoirs need to be safe from leaking. The safety precautions must be identified properly, and the projects must be handled by an expert to ensure the successful deployment of the CCS projects.

The CCS projects in Malaysia are still at an embryonic stage. In an effort to raise awareness, CCS courses have been introduced to Malaysian universities in 2013, and are currently being offered at Universiti Tenaga Nasional (UNITEN), Institute of Technology Petronas (UTP), National University of Malaysia (UKM), and the University of Technology Malaysia (UTM) [33].

3. Pedogenic CO_2 Sequestration

The atmosphere contains approximately 730 G tonnes of carbon. By contrast, the oceans provide a reservoir for approximately 38,000 G tonnes [34]. The upper 100 cm of soil is reservoir for 1500 G tonnes of organic carbon and land-plant biomass (belowground within root system) contains ~500 G tonnes carbon [34]. In addition, soil's pedogenic carbonate is a reservoir for 750–950 G tonnes of carbon [35]. Accordingly, soil organic matter and pedogenic carbonates, as the hosts for organic and inorganic carbon, respectively, are a major terrestrial sink for carbon, containing three times as much carbon as aboveground plant biomass [15]. Engineering soil, through enhancement of the soil organic carbon and pedogenic carbonate stocks, has proven to be a potentially effective method for atmospheric CO_2 removal [14–21,36–42]. Sequestration of CO_2, in soil, occurs in organic and inorganic formats.

3.1. Organic CO_2 Sequestration

Soil organic carbon stock and its potential for further sequestration has been well researched, and the focus for achieving goals which were set to tackle issues associated with global warming outlined in frameworks, such as COP21 [43–50]. Sequestration of carbon organically, in addition to the conservation of existing soil carbon stocks, are two important pathways contributing significantly towards the COP21's target of maintaining global temperature increase less than 2 °C [50]. Forest soils are an important reservoir for organic carbon sequestration in Malaysia. Malaysia has a forest area of 17.7 M ha, of a total land area 330,803 km^2 (33 M ha), i.e., 53.64% is forest compared to the total area of Malaysia. It is possible for Malaysia to sequester 15 tonnes of CO_2 $ha^{-1}year^{-1}$ in forest soil [7]. However, climate change and stagnating crops may lead to reduction in soil organic carbon stock [51], making it an uncertain sink for carbon and an unstable method for atmospheric CO_2 removal.

3.2. Inorganic CO_2 Sequestration

Soil inorganic CO_2 sequestration, as inorganic carbon, has the potential to be an effective method for atmospheric CO_2 removal [14,15,18–20,36,37]. Calcium content and availability of CO_2 in the substrate are two important factors controlling the formation of pedogenic carbonates which are predominately composed of the mineral calcite ($CaCO_3$). Calcium is derived naturally from the weathering of silicate minerals (plagioclase feldspars, pyroxenes etc.) that commonly occur in basic igneous rocks (e.g., basalts) or artificial calcium silicate and hydroxide minerals present in concrete and cement [14,16,52]. In addition, fly and bottom ashes contain calcium (as CaO) required for inorganic CO_2 sequestration [53]. Decomposition of organic acid anions [18], which combine with other biogenic carbon inputs in soils to produce CO_2 as the ultimate product of aerobic decomposition [36]. A proportion of the CO_2, depending on the pH, partitions into the soil solution as bicarbonate or carbonate [36]. Calcium in solution (derived from weathering of silicate minerals) reacts with dissolved CO_2 to form carbonates ($CaCO_3$). This leads to removal of atmospheric CO_2 and formation of $CaCO_3$ in soil as a stable sink [14,16–20,36,54]. Power et al. [55] identified ultramafic and mafic mine tailings as alternative materials required for inorganic CO_2 sequestration. Unlike organic CO_2 sequestration, once $CaCO_3$ is formed in soil, it stays as a stable sink which could only be removed naturally through dissolution, and entering surface and groundwater systems [36].

Inorganic carbon sequestration in Malaysia has not been extensively studied, and the country's potential for using inorganic carbon sequestration for atmospheric CO_2 removal is unknown. Only recently, Syed Hasan et al. [56] investigated the potential of gold mine waste for inorganic carbon sequestration, and realised that there is great potential for the materials to be used as a tool for passive CO_2 removal. Malaysia is a developing country, and will see a large volume of demolition and construction activities, where the impact and opportunity for a national carbon budget in redevelopment can be considered. Demolition provides calcium-rich material, and redevelopment provides a unique chance to integrate inorganic CO_2 sequestration into the design of future structures. In addition to the demolition waste in Malaysia, other sources of Ca include by-products such as coal ash (bottom and fly ash) waste from power plants, and basalt quarry fine containing calcium-rich material necessary for inorganic CO_2 sequestration.

Sufficient soluble Ca^{2+}/Mg^{2+} in soil results in carbonate precipitation [57]. Accordingly, one of the main limiting factors for inorganic CO_2 sequestration is exhaustion of calcium sources in soil. According to Jorat et al. [54], occupation of soil void spaces as a result of calcite precipitation would eventually lead to termination of inorganic CO_2 sequestration process. Concerns have been raised on flood risk at urban sites engineered for inorganic CO_2 sequestration, due to soil pore spaces clogging as a result of calcite precipitation [36]. Reduction of permeability was observed on soil samples treated artificially with microbial induced calcite precipitation (MICP) (e.g., Al Qabany and Soga [58]). Due to annual heavy rainfalls in Malaysia, which could lead to flooding, prior to large-scale deployment of the inorganic CO_2 sequestration technique, flooding risk assessment must be conducted using pilot studies. MICP has also been demonstrated to increase ground strength through cementation of soil particles [58]. Where enhancement of ground strength is preferable, inorganic CO_2 sequestration could be designed into the ground to couple CO_2 capture with ground improvement. For engineering practice, inorganic CO_2 sequestration could be used as a natural process to stabilise strength in soil.

Groundwater stores carbonate in the form of bicarbonate [59], which is considered a long-term effect of inorganic CO_2 sequestration. Formation of $CaCO_3$ in soil, as a result of inorganic CO_2 sequestration, is known to increase the environment's pH [15–20], and can be used as a technique to reduce acidity of soils with low pH. If inorganic CO_2 sequestration is implemented at a large scale, monitoring of groundwater bicarbonate is required. Contamination is an important factor which should be taken into account when choosing source of calcium required for inorganic CO_2 sequestration. This is particularly important when dealing with demolition concrete waste, and fly and bottom ashes, as contaminated leachate might cause extensive (and often permanent) groundwater contamination. Contamination analysis must be conducted on the calcium sources prior to deployment.

4. Industrial Waste in Malaysia

Various types of industrial wastes are being generated in Malaysia, and only three types related to this study are being presented in this section. Chemical composition of selected samples from the industrial wastes are presented in Table 1.

Table 1. Typical chemical composition of demolition concrete waste, basalt, and fly and bottom ash samples from Malaysia.

Element	Demolition Concrete Waste (wt %) [60]	Basalt (wt %) [61]	Fly Ash (wt %) [62]	Bottom Ash (wt %) [62]
CaO	70.88 ± 9.22	11.08	4.81	9.8
SiO_2	20.68 ± 6.47	47.17	51.8	42.7
Al_2O_3	3.43 ± 1.52	16.78	26.5	23
FeO	-	8.89	-	-
Fe_2O_3	1.38 ± 0.73	-	8.5	17
Na_2O	0.06 ± 0.01	2.2	0.67	0.29
MgO	1.99 ± 0.19	8.07	1.1	1.54
K_2O	0.67 ± 0.13	1.26	3.27	0.96
TiO_2	0.11 ± 0.04	1.13	1.38	1.64
MnO	0.06 ± 0.55	0.11	-	
P_2O_5	0.06 ± 0.02	0.1	0.9	1.04
Rb_2O	0.01 ± 0	-	-	-
SrO	0.04 ± 0.01	-	-	-
ZrO_2	0.02 ± 0.01	-	-	-
BaO	-		0.12	0.19
SO_3	0.61 ± 0.47	-	0.6	1.22
LOI	-	3.02	-	-

4.1. Demolition Concrete Waste

Development in the construction sector has resulted in the significant production of solid waste which, in turn, could create environmental-related issues. Due to rapid development in the economy, population growth, and inadequate disposal land and infrastructure, solid waste has become Malaysia's most critical environmental issue [63]. In particular, inappropriate deposition of demolition waste has resulted in serious environmental issues in Malaysia [64]. Only 15% of overall demolition and construction waste in Malaysia are recycled annually, which is far behind countries such as Singapore, Germany, and South Korea, with the rate of 50%–75% [65]. Malaysia generates 26,000 tonnes of construction and demolition waste daily, leading to the generation of nearly 10 million tonnes of wastes annually [65]. According to Nagapan et al. [66], a study of 30 demolition sites in Malaysia showed that concrete comprised 12.3% of the total demolition waste. Considering the total annual generation of demolition waste, a minimum of 1.2 million tonnes of concrete waste is being produced in Malaysia annually. Demolition concrete waste comes in various sizes and shapes, depending on its origin. The size varies from clay size to large blocks which, in the latter case, must be further crushed to provide larger surface area.

4.2. Basalt Quarry Fine

Basalt quarries for aggregate production generate two types of residues: (i) aggregates produced during crushing and milling operations, which are used as fine aggregates by the construction sector, and (ii) fines remain from crushing and milling operations, which have no commercial value to be used as aggregate for construction. Based on the information acquired from operational basalt quarries in Malaysia, clay size fines account for 18–20 wt % of the aggregate production, and are commonly being deposited in large quantities at quarries. Recommendations have been given on suitability of basalt quarry fines for Portland cement production (e.g., [67]); however, where limestone is abundant (as in Malaysia), basalt quarry fines often would not be used as raw material for Portland cement production.

In the Malay Peninsula, basalt is found as occasional outcrops [68], for example, at Baserah, Pahang in Malaysia [69] (Figure 2). According to Hamdan et al. [70], basalt in Pahang spreads over an area of around 30,000 ha. Ghani et al. [61] reported existence of basalt in Kuantan, Perhentian, Redang Islands, and mainland Terengganu (Figure 2). According to the [71], three active basalt quarries operate in Malaysia (two in Johor and one in Sabah) (Figure 2). Basalt aggregate production from these increased significantly from 27,400 tonnes in 2010, to 344,930 tonnes in 2017 [71]. Considering the 18–20 wt % quarry fine production, it is estimated that Malaysia produces 62,000–69,000 tonnes of basalt quarry fines, with no current commercial value.

4.3. Coal Ash

Production of electricity in Malaysia highly relies on six coal-fired thermal power plants [72] (Figure 2), which are associated with the generation of fly and bottom ashes in significant volumes. In Malaysia, fly and bottom ashes are commonly deposited in uncovered landfills, which impose significant environmental issues. According to Rafieizonooz et al. [73], Malaysia produces 6.8 and 1.7 million tonnes of fly and bottom ashes annually, respectively. Studies show the suitability of fly and bottom ashes, in Malaysia, for construction purposes (e.g., [74–77]). However, these are still at research level, and fly and bottom ashes have not been utilised at industrial scale in construction activities in Malaysia. Muhardi et al. [62] reported fly ash size <0.04 mm and bottom ash size 0.07< <11 mm.

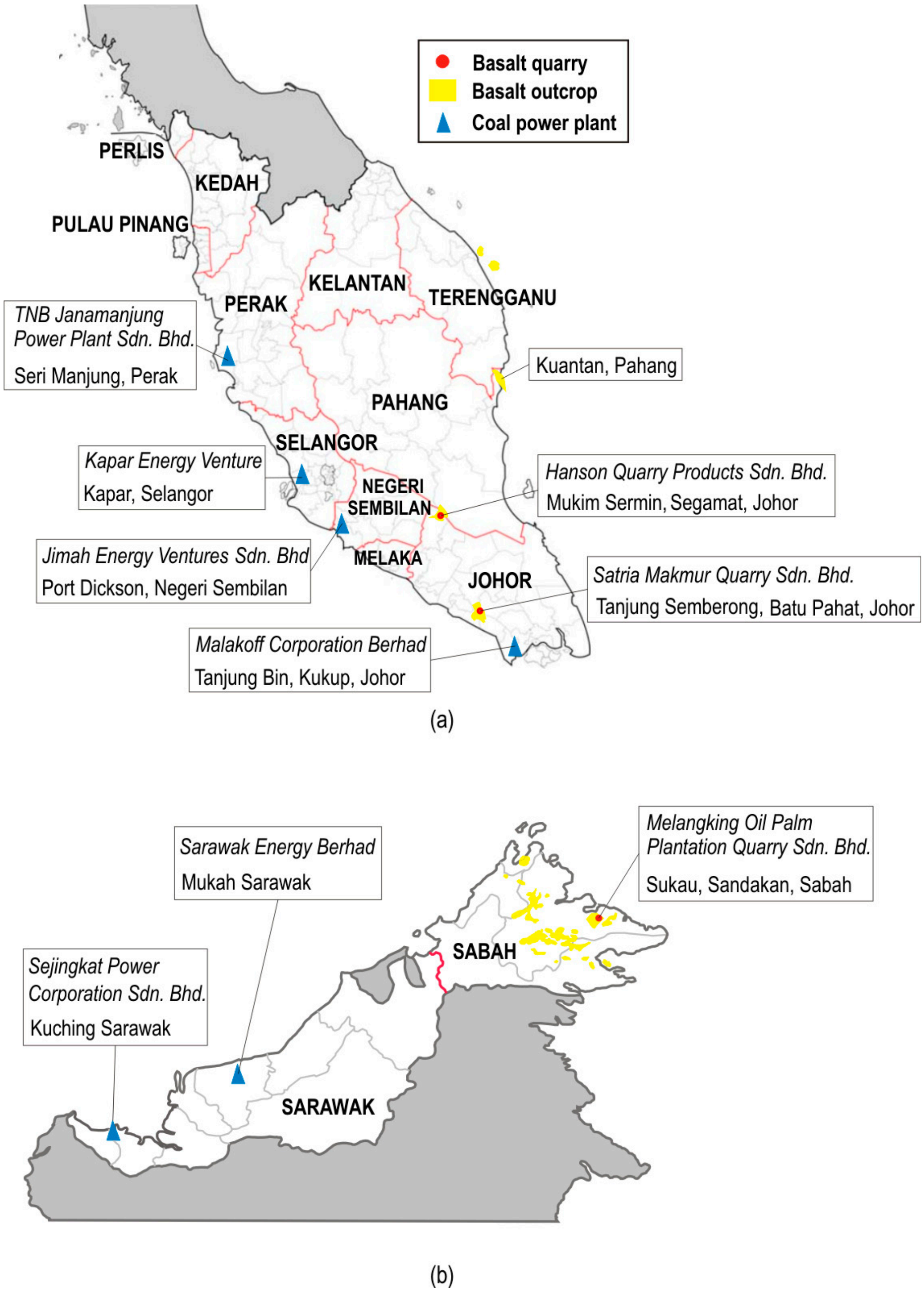

Figure 2. Map of (**a**) Peninsular Malaysia (adopted from https://openclipart.org/detail/290360/peninsular-malaysia-blank-map) and (**b**) East Malaysia showing locations for basalt quarry, basalt outcrop, and coal power plant. Information regarding basalt quarries and outcrops was derived from Department of Mineral and Geoscience Malaysia [71] and, regarding coal power plants, was derived from https://endcoal.org/global-coal-plant-tracker/.

5. Malaysia's Capacity for Using Soil Mineral Carbonation

Malaysia, as a developing country, is anticipating an increase in construction and demolition activities in the future [78]. In Europe, the life of concrete buildings is 40–50 years, in contrast to 25 years in a tropical country such as Malaysia. Considering Malaysia's increasing CO_2 emission and growing construction and demolition waste figures, there is an abundant scope for inorganic CO_2 sequestration to be exploited and implemented, in order to utilise demolition waste for atmospheric CO_2 reduction. Washbourne et al. [19] investigated a site in the United Kingdom containing demolition waste, and showed that the top 10 cm of soil at the site sequestered 85 tonnes CO_2 $ha^{-1}year^{-1}$. Manning et al. [79] measured sequestration capacity of 6 tonnes CO_2 $ha^{-1}year^{-1}$ for the top 10 cm of soil at the site containing 50% dolerite fines (which has similar material composition to basalt) and 50% compost. Considering annual generation of nearly 1.2 million tonnes of demolition concrete wastes [65] and 62,000–69,000 tonnes of basalt quarry fines [80], these materials can be used for inorganic CO_2 sequestration in Malaysia, if the function is designed into the first 10 cm of land associated with the country's future developments. Taking the availability of demolition concrete waste and basalt quarry fines into consideration, and assuming an application rate of 100% demolition concrete waste and 50% basalt + 50% compost, Malaysia has the capacity to annually establish 1043 and 85 ha of land suitable for inorganic CO_2 sequestration using demolition concrete waste and basalt quarry fine, respectively. Accordingly, taking into account the sequestration rates for demolition concrete waste and basalt quarry fine, 89,000 tonnes of CO_2 can be captured annually in Malaysia (Table 2). This figure accounts for 0.03% of the country's projected total CO_2 emission in 2020.

Table 2. Annual production for the three types of industrial waste in Malaysia suitable for inorganic CO_2 sequestration, area of land that could be engineered, and the country's annual CO_2 sequestration capacity.

Material	Annual Production (tonne)	Engineered Area (ha)	Annual CO_2 Sequestration Capacity (tonne)
Demolition concrete waste	1,200,000	1043	88,655
Basalt quarry fine	62,000– 69,000	85	510
Fly ash	6,800,000	7907	176,800
Bottom ash	1,700,000	1143	331,500
		Total = 10,178	Total = 597,465

Annual CO_2 sequestration capacity of *in-situ* soils containing fly ash and bottom ash have not been investigated. However, based on a laboratory study, Montes-Hernandez et al. [53] reported maximum CO_2 sequestration capacity of 26 kg for one tonne of fly ash. In addition, based on another laboratory study, Kim and Lee [81] observed maximum CO_2 sequestration capacity of 195 kg for one tonne of bottom ash. If the 6.8 and 1.7 million tonnes of fly and bottom ashes, respectively, being produced annually in Malaysia [73] would be used for the first 10 cm of land associated with the country's future developments (e.g., using lands associated with construction of highway [14,82]), more than 9000 ha of land could be designed for inorganic CO_2 sequestration, and 500,000 tonnes of CO_2 could be captured. This figure accounts for 0.2% of the country's projected total CO_2 emission in 2020.

Temperature is a parameter that controls the kinetics of mineral carbonation reaction. An increase in temperature is known to increase reaction kinetics [83]. Accordingly, in a country like Malaysia, with a tropical climate, the mineral carbonation rate should be higher than compared to the United Kingdom. To accurately quantify the differences in rate, similar small-scale experiments to those in the United Kingdom should be conducted, and annual sequestration capacity of the by-products should be measured.

Considering the existing obtainable price for CO_2 recommended by the European Emissions Trading Systems (EU ETS) found from the European Energy Exchange (EEX) which, on 8th August 2015 stood at €7.94/tonne CO_2, the management of land to sequester 89,000 tonnes of CO_2 using concrete demolition concrete waste/basalt quarry fine and 500,000 tonnes of CO_2 using fly/bottom ash could have an equivalent price of nearly €4,700,000 for CO_2 sequestration annually. The use of these mineral-based materials contributes to Malaysia's targets, and offsets the carbon costs associated with cement manufacture and mining.

6. Conclusions

After signing the COP21, Malaysia is looking for solutions to tackle developing annual CO_2 emissions. Carbon capture and storage is very new to the country, and apart from two notable examples, remaining efforts in the direction of CO_2 sequestration have been limited to small-scale research studies. In this study, our hypothetical analysis shows that inorganic CO_2 sequestration could be a suitable solution for Malaysia's CO_2 emissions. We have identified three main by-products in Malaysia containing calcium, which is required for inorganic CO_2 sequestration, namely, demolition concrete waste, basalt quarry fine, and fly and bottom ashes. Using the by-products for climate mitigation also reduces the country's annual waste productions and minimises negative environmental impacts associated with often unsuitable deposition of the by-products. Our analysis shows that 10,178 ha of readily available lands, associated with the country's future developments, could be engineered annually using the by-products being produced in Malaysia, leading to the sequestration of 597,465 tonnes of CO_2 year^{-1}. This accounts for 0.23% of the country's projected total CO_2 emission in 2020, with a potential annual economic benefit of €4,700,000.

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