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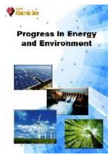

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Review Article

A Current Review and Global Benchmark on the Challenges and Prospect of Air Pollution Mitigation in Malaysia

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Abstract

The paper delves into the global air pollution issue, with a particular focus on Malaysia as a member of the ASEAN community. It underscores that air pollution is not merely a statistical concern but a daily reality impacting public health and the environment. Over time, there has been a significant increase in mortality and hospitalization rates attributed to air pollution. Human activities, including industry processes, transportation, and waste management, are identified as major contributors to air pollution. The paper discusses Malaysia's governmental efforts to address air pollution, encompassing air quality monitoring and control systems, environmental protection acts, promotion of alternative green energy sources, and carbon emission control measures. Despite the potential of renewable energy sources such as wind and hydropower, their limitations in fully replacing traditional energy sources are highlighted. Furthermore, the paper identifies methods to control urban air pollution by reviewing successful strategies implemented in other developed countries, such as advanced public transport systems and vehicle registration and age limitations. In conclusion, this paper provides valuable insights into the air pollution issue in Malaysia and offers suggestions for controlling and mitigating its impact, thus, contributing towards cleaner air and healthier environments.

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1 Introduction

Air pollution refers to the harmful or toxic chemical or particle that exists in air that would damage the health of humans, animals, and natural ecosystem. Data from the World Health Organization (WHO) had reported that the air pollution had to been responsible for the death of seven million live annually in the world [1]. Based on a study, it had been found out that air pollution exposure and poverty had a strong relationship. By using WHO fine particulate matter (PM) thresholds, data had shown that 7.3 billion people globally had been directly exposure to unsafe PM2.5 pollutant concentration annually [2]. The people from low and middle countries were suffering the most from this air pollution issue, among nine out of ten were inhaling pollutants in air which had exceed the WHO's guideline [3].

The air pollution had caused a huge increase in health problems in humans, which had directly soar of health costs. Air pollution had a serious impact on human health, Great Smog in London in 1952 was one of the examples, where tens of thousands of lives had been killed in this crisis [4]. Moreover, studies found out that short term exposure to air pollution could lead to significant rise in mortality from all-natural causes and main cardiopulmonary causes [5]. In terms of morbidity, hospitalization of respiratory had been found to increase with the increase of coarse particles. Airborne particulate matter of the diameter of 10 µm (PM10) is able to enter the lungs while particles of PM2.5 which had diameter of 2.5 µm is able to further penetrate distal lung segment including the alveoli [6,7,8]. This means that the PM2.5 is able to enter the bloodstream and negatively affect the organ such as brain, heart, liver and kidney. The risk of hypertension could be associated with air pollution, PM2.5 had been proven to increase the risk due to increase of blood pressure which caused by the coarse and fine particulates [9]. In Malaysia, 10.35% of death was led by respiratory-related illness in the year of 2011 [10]. This issue could be associated with the increase of PM10 concentrations in Asia.

The impact of air pollution not only on human health, but it would also increase countries' economic burden [11]. In a study in the Republic of Macedonia, the health effect caused by air pollution had an economic cost of 253 million European Dollar which represents 3.2 % of that country's gross domestic product (GDP) [12]. Another study by the world bank had estimated that a decrease of 20 % of PM2.5 will increase 16 % of employment growth and 33 % of labour productivity growth rate globally [13]. Moreover, the economic growth of a country had been found to be associated with the air pollution issue [14].

Malaysia, one of the developing countries in Asia which had focus on industrialization had face severe air pollution issue recent time [15]. A study had been done in Klang Valley Malaysia which is one of the biggest industry areas in Malaysia, had found out that air pollution had increase the hospital admission for cardiovascular and respiratory [16]. The death rate associate with air pollution in mainland Southeast Asia had shown significant rising between the year 2000 and 2019 [17]. From one of the air quality monitoring systems, it had been found out that the average PM2.5 concentration in Malaysia was 3.5 times higher than the guideline set by the WHO [18]. Thus, this paper is aimed to provide valuable insights and recommendations to address the pressing environmental concern of haze in Malaysia, underlining our commitment to a well-founded and methodical review.

The remaining paper is structured into several key sections to provide a comprehensive analysis of air pollution issues and mitigation efforts in Malaysia. Section 2.0 delves into the factors affecting air quality, exploring various contributors such as industrial activities, transportation, and waste management practices. In Section 3.0, Malaysia's endeavours in combating air pollution are examined, highlighting governmental initiatives, air quality monitoring systems, and efforts to promote alternative green energy sources and carbon emission control. Section 4.0 addresses the limitations and suggestions for improvement, with subsections focusing on renewable energy strategies and methods to mitigate urban air pollution. Within these subsections, specific challenges and recommendations are outlined to guide future efforts in enhancing air quality management. Finally, Section 5.0 presents the conclusion, summarizing the key findings of the paper and emphasizing the importance of concerted actions to address air pollution issues in Malaysia for the betterment of public health and environmental sustainability.

2 Factors affecting air quality

Air pollution may come from various sources of natural incidents and human activity, each contributing on the quality of air. Natural occurrences, such as volcanic eruptions, wildfires, and dust storms, inject particulate matter and gases into the air, disrupting local and even global air quality patterns. Meanwhile, human activities significantly contribute to the pollution burden [19]. Industrial processes release a plethora of pollutants, including sulphur dioxide (SO_2), nitrogen oxides (NO_x), volatile organic compounds (VOCs), and particulate matter arising from combustion, chemical reactions, and manufacturing operations. Transportation systems, particularly vehicles powered by fossil fuels, emit copious amounts of pollutants like carbon monoxide (CO), nitrogen dioxide (NO_2), and fine particulate matter, crowning urban centres with the notorious haze of smog. Agricultural practices, such as livestock farming and crop burning, release ammonia (NH_3), methane (CH_4), and other pollutants into the air, exacerbating regional air quality issues. Moreover, household activities, from cooking with solid fuels to heating with wood or coal, contribute to indoor and outdoor air pollution burdens, impacting both human health and the environment. As the collective footprint of these sources continues to grow, so too does the urgency to address air pollution through holistic approaches that encompass regulation, innovation, and societal change. An overview of the issue is presented shown as Fig. 1.

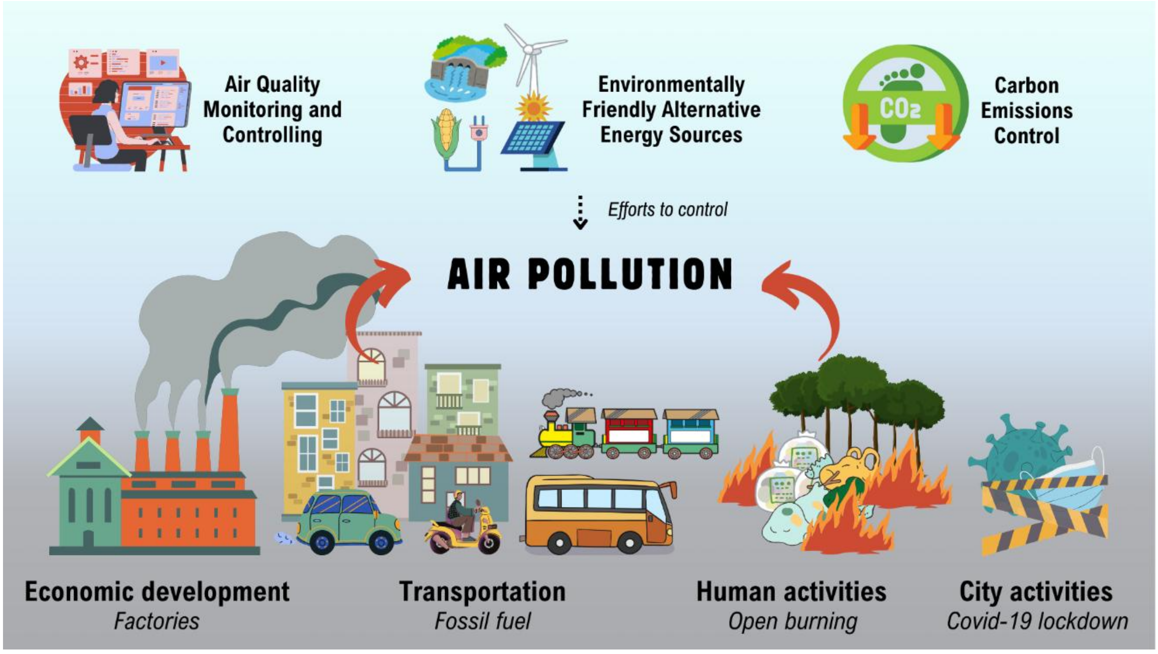

Fig. 1. Overview of outdoor air pollution problems and ways to overcome.

Air Pollutant Index (API) was established by the Malaysian Department of Environment in the year of 1996 with 68 air monitoring stations in Malaysia. Air monitoring stations can detect the concentration of PM2.5, PM10, CO, NO_2, SO_2, and ozone in the atmosphere, those concentrations will then be transformed into API to determine the pollution level. Every API result observed is critical for air quality management, through monitoring of those data, the air pollutant source could be identified, and the country decision-maker could implement suitable rules and regulations to restrict activities and industries that leak to API increase, a necessary step to reduce and improve the air quality could be taken. From twenty years of data visualized in Sarawak from the year 2000 to 2019, the frequency of API value excesses the “good” limit had a significant increase within the observed range, which could be due to many factors and activities occurring in that state [20]. To further identify the major contributor of air pollution in Malaysia, Fig. 2 illustrated the amount of greenhouse gases (GHG) emitted in by sector in Malaysia, the GHG emissions mainly dominated by power industry and fuel industry, the emission data had clearly significant increase since the year 1990, other industry that contributed to the GHG emission include transportation, construction, and fuel exploitation.

City activity has a huge impact on the city’s air quality, this could be reflected in the lockdown of Wuhan, China due to the COVID-19 outbreak. The air quality in that city had been improved during the period when the PM2.5 had been decreased by 36.9 %, and other pollutants such as NO_2, also had shown a significant decrease [22,23]. The same situation was observed in South Korea, where PM2.5 had shown a decreasing trend during the COVID-19 outbreak period [24]. The implementation of the Movement Control Order (MCO) during the outbreak in Malaysia led to a reduction of 58.4 % in overall PM2.5 concentration based on 68 built air quality monitoring stations [25]. This trend also had been shown in the world's top 50 polluted capitals globally by WHO, PM2.5 concentration had a significant difference before and after the lockdown [26]. This shows that human daily activities such as driving, and industry have contributed to the emissions of pollutants that lead to air pollution.

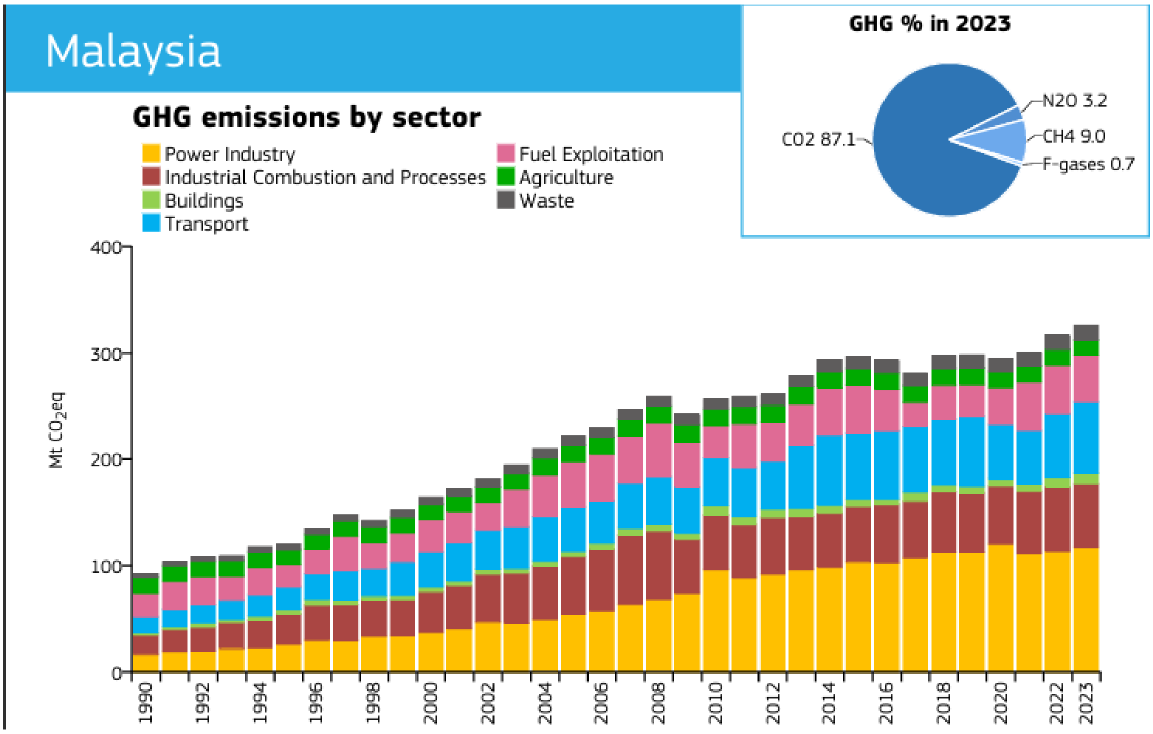

Fig. 2. GHG Emission in Malaysia by Sector from 1990 to 2024 [21].

Open burning is one of the most serious contributors to the occurrence of haze in a few ASEAN Countries like Malaysia and Singapore. As stated before, the PM2.5 concentration in Malaysia had shown a significant reduction during the MCO period, however, in the Kota Damansara area the reduction only observed in CO by 48.7 %, the PM 2.5 and PM10 concentration had increased by 60 % and 9.7 % respectively, this trend is most likely due to the open burning activities observed in that residential area [27]. Severe open burning in Indonesia has caused haze in Malaysia and Singapore, which caused a huge increase in daily PM2.5 levels [28]. An investigation in Hatyai, a Southern city of Thailand, by using chemical mass balance, it had been confirmed that the haze originated from Indonesia with the influence of aerosols which caused an increase in PM2.5 level in that area [29]. Those chemical compound that assists in the haze included organic carbon, elemental carbon, water-soluble organic carbon, water-soluble ions, element tracers, heavy metals, and sixteen polycyclic aromatic hydrocarbon components which had been found through analysis of PM2.5 samples in that research area.

The relationship between economic development and air quality has been studied in previous studies. Research found that, in low-income countries, the rise in GDP would cause changes in economic structure which will increase the emission of gasses such as SO_2, smog, and carbon dioxide (CO_2) [30,31]. One of the reasons for this is that the increase in energy consumption would lead to CO_2 emissions toward the region and world. This could be seen in data that indicate the most pollutant city in Malaysia was Klang, Selangor, while the cleanest city was Bongawan, Sabah while Klang is one of the most advanced industries equipped in Malaysia (Malaysia Air Quality Index (AQI) and Air Pollution Information [18]. The energy demand rose with Malaysia's speedy economic growth due to the higher demand and consumption of fossil fuel energy, which resulted in increased carbon emissions [32]. Additionally, Sarawak aims to become a developed and high-income state by 2030, the industries' activities have a significant increase to achieve this goal, and the increase of the API index from the year 2000 to 2019 could be addressed to this 2030 goal set by the Sarawak government [20]. This also be identified through the increase in the country's GDP with is increase in carbon and GHG emissions as in Table 1.

According to the data from the Road Transport Department (JPJ) Malaysia, the total active motor vehicles registered in Malaysia had reached 21,709,492 as of the year 2022, while the total population in Malaysia was 32.5 million [33,34]. At that time most vehicles were still traditional fuel vehicles instead of electric vehicles (EV). The number of active vehicles was found to be associated with the contribution of air pollution. A study in Kuala Lumpur, Malaysia found that PM10 emissions from vehicle exhaust had a total amount if 1,029,883 kg in the year 2014, at the same time the CO and nitrogen monoxide (NO) emitted was 14,605 kg and 5,726 kg respectively [10]. Additionally, the PM10 concentration in the Klang Valley area ranged between 80 – 100 µg/m³ from the year 2000 to 2009, this concentration is almost 4-fold to the threshold value set by the New Malaysia Ambient Air Quality Standard (NMAAQS) and WHO which are 40 and 20 µg/m³ respectively [35]. The excessive high value is expected due to rapid urbanization and high conventional fuel motor vehicle usage in that area. The study also indicates the CO emitted in Malaysia was highest among ASEAN countries.

Fossil fuel is one of the world's most relied-on energy sources, the use cases of fossil fuel include heating, transport, and electricity. In most Middle Eastern countries and some Asia countries that produce and export fossil fuel, the government has been continuously providing subsidies for the consumption of fossil fuel by the people and industry in that country, which causes a low-price consumer fossil fuel product [36]. The electricity generated in Malaysia mainly depends on three different types of fossil fuels which are coal, natural gas, and fuel-oil [37]. Coal is a type of fossil fuel that produces dirty GHG during combustion due to its complex structure. SO_2, NO_x, particulates, CO_2, mercury and other heavy metal were some of the harmful pollutants that would produce during the electricity generation process, combustion [38,39]. In term of carbon emission, the carbon emitted from coal is double of that produced by natural gases in combustion [40]. Unfortunately, as of the year of 2020, more than 50 % of electricity in Malaysia was generated from coal, and the amount of coal used even more then 20 years ago [41]. As in Table 1, it had been shown that the coal consumption the carbon and GHG emission had shown increase trend with the consumption of coal.

Apart from those physical causes causing the air pollution worst in Malaysia, the outdated legislation might become another factor that contributed to bad air quality. The excessive dust produced in construction industries had significant negative effect on air quality, and major contributor to carbon emission. The Malaysia government had implement various type of rule and regulation in controlling the air pollution caused by this industry, however, the almost no cases reduction observed [42]. This suggested that the current Act are not working, which suggesting revised of those acts such as Environmental Quality Act (EQA) 1974, Construction Industry Development Board of Malaysia Act 1994 are required [43].

Table 1. Data on carbon, GHG emission, coal and fossil fuel consumption and GDP in Malaysia [13,44,45,46].

Year	Carbon emissions (million tons)	GHG emissions (million tons)	Coal consumption (TOE)	Fossil fuel consumption for energy generation (TOE)	GDP (billion USD)
2013	242.16	169.28	15.067	0.392	323.27
2014	245.32	202.09	15.357	0.269	338.06
2015	235.70	187.53	17.406	0.101	301.35
2016	252.06	377.38	18.886	0.157	301.25
2017	248.20	360.65	19.312	0.099	319.11
2018	267.08	384.04	21.122	0.017	358.79
2019	269.15	396.11			365.18
2020	259.48				337.34
2021	256.04				372.98

3 Malaysia's efforts in controlling air pollution

Air pollution remains a significant global issue around the world and getting worsen with the industry development and population growth that consequently into serious implications for public health and the environment. According to the global air quality report released by IQAir [18] as shown in the Fig. 3, only 10 out of 134 countries and regions met the WHO guideline for PM2.5 levels of 5 µg/m³, emphasizing the widespread nature of the problem. Among these regions, Asian countries are especially affected, with Bangladesh (79.9 µg/m³), Pakistan (73.7 µg/m³) and India (54.4 µg/m³) ranking as the top three most polluted countries. These nations face high pollution due to factors like industrial emissions, vehicular pollution, crop burning and population growth. In contrast, several regions in Europe, North America and Oceania have successfully maintained lower PM2.5 levels through stricter environmental regulations and a shift towards cleaner energy. Malaysia, ranking as the 38th most polluted country globally with an average PM2.5 concentration of 22.5 µg/m³, also holds the 7th spot in Southeast Asia, highlighting the country's ongoing struggle with air quality issues.

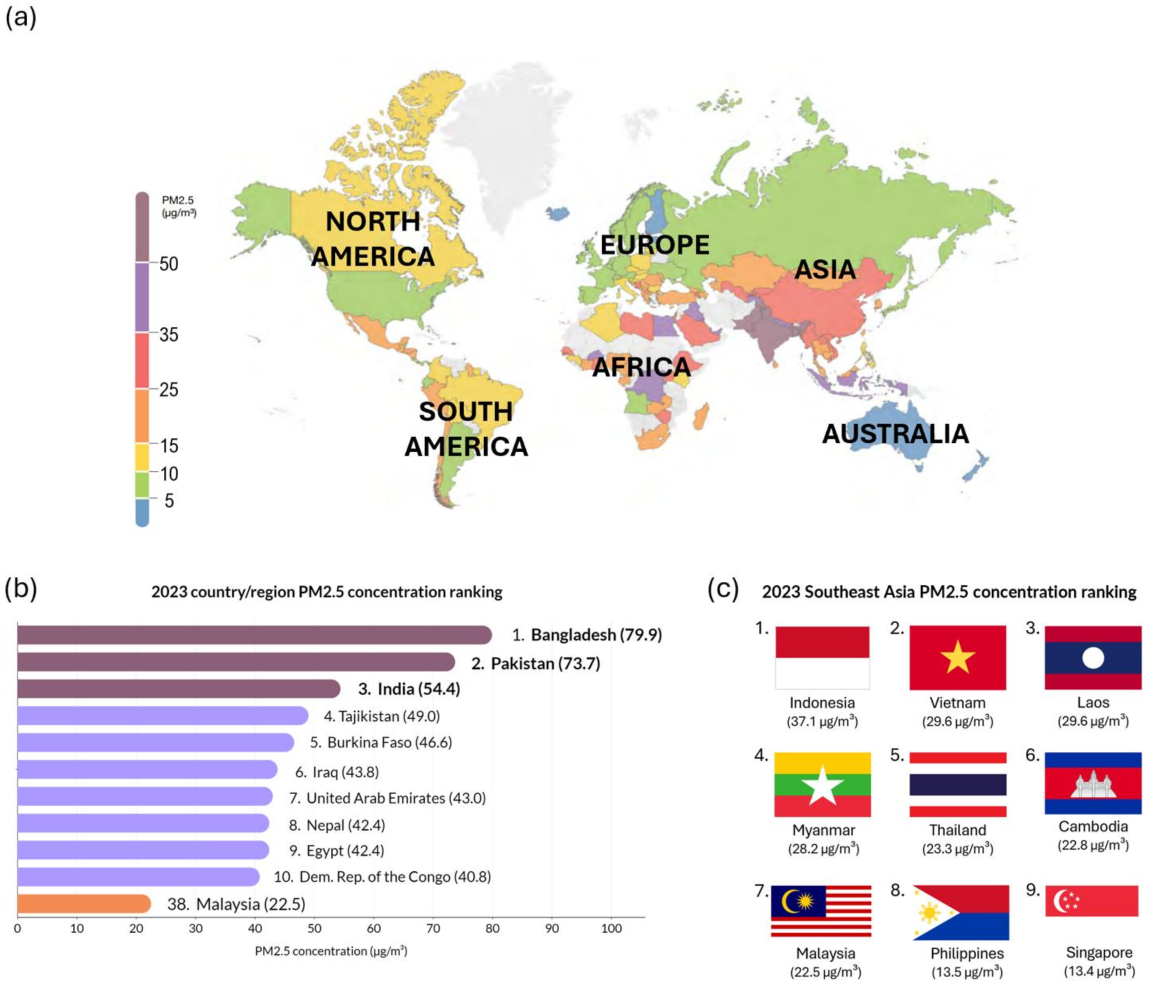

Fig. 3. (a) Global PM2.5 Map, (b) Global PM2.5 concentration ranking and (c) Southeast Asia PM2.5 concentration ranking, in the year 2023 [18].

Based on the statistics, it is clear that countries in Europe, North America, and Oceania experience significantly lower levels of air pollution, with significantly lower PM2.5 concentrations. For example, nations like Iceland, New Zealand and Australia maintain average PM2.5 levels well below the WHO guideline of 5 µg/m³. Their cleaner air quality can be attributed to robust environmental regulations and comprehensive air quality management systems. For instance, Clean Air Act (CAA) introduced by the

United States [47] as well as strict ambient air quality standards implemented in Europe play a critical role to protect human health and maintain good air quality via regulating emissions of harmful air pollutants [48]. Strict industrial and vehicular emission standards, coupled with investments in renewable energy and advanced pollution control technologies such as carbon capture, utilization, and storage systems, have also contributed to reduce pollution levels. Moreover, these countries emphasize sustainable urban planning and advanced public transportation systems, reducing reliance on personal vehicles and further mitigating air pollution. Their proactive policies and integration of sustainable practices have allowed them to maintain cleaner air, setting a benchmark for other nations. Conversely, Malaysia continues to struggle with high pollution levels, largely due to its reliance on fossil fuels, underdeveloped green energy infrastructure, inadequate carbon emission control technologies, weak environmental enforcement as well as low public awareness and cooperation.

In Southeast Asia, Malaysia's air quality is relatively better than many of its regional counterparts, such as Indonesia, Vietnam and Thailand. The air quality in many Southeast Asian countries has been largely impacted by emissions from industries, vehicle pollution and open burning activities. In the year 2023, the situation is made worse by climate conditions, particularly the prolonged dry season caused by the delayed onset of rains due to El Niño [49]. This extended dry period has intensified forest fires, further deteriorating air quality across the region. Compared to its regional peers, Malaysia has managed to maintain a lower air pollution level mainly attributed to several factors, including its stronger air quality regulations and government-led air quality monitoring system. Unlike most Southeast Asian countries, where over 60 % of air quality data comes from non-governmental sources, only 19 % of Malaysia's data is non-governmental, reflecting its strong public commitment to air quality monitoring [18]. Additionally, Malaysia has made efforts to reduce air pollution through initiatives such as National Air Quality Monitoring Network, policies promoting cleaner energy and transportation alternatives. However, Malaysia still faces challenges, including vehicle emissions, rapid industrial growth and slash as well as occasional transboundary haze pollution, which underscores the need for continued and enhanced regional cooperation and domestic efforts to further improve air quality [50].

As Malaysia takes concerted steps to combat the pressing issue of air pollution, this review explores the nation's multifaceted efforts within the context of key international agreements. Notably, Malaysia is a party to agreements such as the United Nations Framework Convention on Climate Change (UNFCCC), the Convention on Long-Range Transboundary Air Pollution (LRTAP), and the ASEAN Agreement on Transboundary Haze Pollution. While these agreements vary in their primary focuses, they collectively underscore Malaysia's commitment to not only safeguarding its local environment but also collaborating on a global scale to address transboundary environmental challenges [51,52,53].

Beyond the diplomatic commitments, the benefits of controlling air pollution are far-reaching. Improved air quality translates to enhanced public health, mitigated climate change impacts, and sustainable development. The importance of Malaysia's endeavours lies not only in fulfilling international obligations but also in cultivating a healthier, more resilient nation that actively contributes to the collective global pursuit of a cleaner and more sustainable future. This paper seeks to unravel the interconnectedness between Malaysia's domestic initiatives and its engagement in international agreements, highlighting the significance of these efforts in fostering environmental well-being on both local and global scales.

3.1 Air quality monitoring and controlling

Monitoring air quality in Malaysia is a meticulous process overseen by the Department of Environment (DOE), aligning with stringent legislations and employing advanced techniques to safeguard public health and the environment. The DOE operates a comprehensive network of strategically positioned air quality monitoring stations, covering residential, traffic, and industrial areas across the country [54]. These stations utilize sophisticated equipment such as continuous air quality monitoring (CAQM) systems to measure various pollutants, including NO_x, SO_2, CO, ozone, hydrocarbon, particulate matter (PM10 and PM2.5) and ultraviolet. The CAQM employed by the DOE continuously monitors air quality parameters in real-time, providing crucial data for immediate analysis and prompt actions when pollutant levels exceed permissible limits. Additionally, the DOE collaborates with international organizations and utilizes remote sensing technologies to supplement ground-based monitoring, enhancing the accuracy and scope of air quality assessments. Moreover, the government also employs continuous emission monitoring systems (CEMS) and predictive emission monitoring systems (PEMS) to prevent harmful emissions from the industrial process [55].

Key legislations and guidelines, including the Environmental Quality Act 1974 and its subsidiary Ambient Air Quality Standard 2013 and Clean Air Regulations 2014, serve as the foundation for air quality management [56]. These regulations outline stringent standards and permissible limits for various pollutants emitted from industrial, vehicles, and other sources. The DOE ensures compliance with these standards by conducting regular inspections and imposing penalties for non-compliance, fostering a culture of environmental responsibility among industries and stakeholders. Table 2 also summarizes some laws and regulations that have been approved and applied by the Malaysian government to prevent as well as control air pollution. Furthermore, Malaysia's API as shown in Table 3 can provides real-time information to the public and thus enabling individuals to take necessary precautions during periods of poor air quality based on data collected from these monitoring stations [57].

Table 2. Acts and Regulations Related to Air Pollution in Malaysia [58].

Environmental Quality Act 1974 (Act 127) ● a basic framework for environmental management in Malaysia that empowers the DOE to regulate and control air pollution and emissions from various sources
Clean Air Regulations 2014 ● regulate emissions of air pollutants from industrial and commercial activities
Ambient Air Quality Standard 2013 ● establish permissible limits and guidelines for ambient air pollutants to safeguard public health and the environment by ensuring acceptable air quality levels
Environmental Quality (Declared Activities) (Open Burning) Order 2007 ● regulate and control open burning activities by designating certain activities as declared activities
Environmental Quality (Control of Petrol and Diesel Properties) Regulations 2007 ● establish and regulate specific standards and properties of petrol and diesel fuels to reduce harmful emissions from vehicles, ensuring better air quality and environmental protection

Table 3. API Index Malaysia [57].

API	Colour	Status	Corresponding actions
0 – 50	Blue	Good	None
51 – 100	Green	Moderate	None
101 – 200	Yellow	Unhealthy	High-risk people should reduce outdoor activities; general population should reduce vigorous outdoor activities
201 – 300	Orange	Very unhealthy	Old and high-risk people are advised to stay indoors and avoid outdoor activities; general population should avoid vigorous outdoor activities; consult a doctor if feel uncomfortable; face masks should be worn when going out
> 301	Red	Hazardous	Everyone should avoid outdoor activities and follow the instructions from the government; consult a doctor if feel uncomfortable; face masks should be worn when going out

3.2 Environmentally friendly alternative energy sources

Renewable energy refers to sustainable sources of power derived from natural processes that are continuously replenished. Examples include solar energy, harnessed through photovoltaic cells or solar thermal systems; wind energy, generated by wind turbines; hydropower, derived from flowing water in rivers or dams; geothermal energy, tapping into the Earth's internal heat; and biomass energy, produced from organic materials. The transition to renewable energy offers significant opportunities, including reduced GHG emissions, energy independence, and job creation. However, challenges such as intermittency, energy storage limitations, initial high costs of technology implementation, and the need for substantial infrastructure upgrades pose hurdles to widespread adoption. Balancing these opportunities and challenges is crucial for maximizing the potential of renewable energy and achieving a sustainable and resilient global energy landscape [59].

As we all know, Malaysia relies mostly on fossil fuels (coal) for its energy needs. According to a statistic in 2022, around 76.4 terawatt-hours (42 %) of Malaysian electricity was produced from coal [60]. Fossil-fuel based power plant not only emits GHG, but also lead to other environmental issues, such as water pollution. Therefore, Malaysia is actively transitioning into green energy sources to combat air pollution in recent decades. As reported by Malaysian Investment Development Authority (MIDA), renewable energy technologies in Malaysia are thriving in the form of solar energy, hydropower, and biomass [61]. Malaysia is located in the equatorial region, which causes our country to receive abundant sunlight throughout the year. The average solar radiation of Malaysia is around 400 to 600 MJ/m^2 per month [62]. Combining a consistent solar radiation and tropical climate makes Malaysia an ideal location to develop solar energy.

Besides, wave energy as a pivotal component in the shift towards renewable and clean energy sources, encompasses a range of innovative devices designed to capture the immense power within ocean waves. Tidal Energy Converters (TEC), Wave Energy Converters (WEC), Ocean Thermal Energy Conversion (OTEC) systems, and Salinity Gradient Energy (SEG) technologies exemplify this diversity in harnessing wave energy [63]. These technologies offer promising solutions to address energy needs while reducing reliance on fossil fuels, highlighting the potential of wave energy to contribute significantly to the global renewable energy transition. In terms of energy density, certain high-energy zones in Malaysia, with the capacity to provide more than 40 MW h/m, stand out as promising sites for wave energy extraction [59]. These zones, often coinciding with robust monsoon seasons, present a substantial opportunity for the application of wave energy in Malaysia's seas. The prospect of leveraging these high-energy zones not only aligns with the nation's transition to sustainable energy sources but also signifies a strategic step towards reducing reliance on conventional energy and embracing a cleaner, more resilient energy future.

Other than that, biomass energy stands out as a crucial player in the realm of renewable energy. Biomass refers to organic materials, such as wood, crop residues, and animal waste, which can be converted into energy through various processes like combustion, gasification, and anaerobic digestion. Its application in renewable energy is multifaceted, contributing to electricity generation, heat production, and biofuels. Noteworthy, recent studies have demonstrated that Palm Kernel Shell (PKS) and polyethylene can produce up to 15.98 MJ/Nm^3, showcasing the high energy potential of biomass [64]. This underscores biomass's efficacy in generating substantial energy yields. Furthermore, the versatility of biomass energy extends beyond its direct applications, as it also plays a crucial role in waste management and carbon sequestration, making it a sustainable and environmentally friendly option for addressing both energy and environmental challenges. However, challenges persist, encompassing technical intricacies in efficient conversion, financial constraints related to infrastructure development, and the need for heightened social awareness to ensure sustainable and responsible biomass utilization. Balancing these aspects is essential for maximizing the benefits of biomass energy and overcoming hurdles in its widespread adoption [65].

Wind energy emerges as a promising alternative in Malaysia's pursuit of sustainable power sources, influenced by factors such as wind direction, speed, geographical considerations, and techno-economic viability. This comprehensive exploration of wind energy encompasses various turbine generation technologies, focusing on non-conventional ideas like Cross Axis Wind Turbines (CAWT), Vertical Axis Wind Turbines (VAWT), and magnetic-based wind turbines [66]. These technologies offer innovative approaches to enhance efficiency. The discussion spans wind turbine structures, power generation methodologies, assessment techniques, and limitations of existing technologies, providing a holistic view of the wind energy landscape. The research findings highlight a considerable potential for wind energy in Malaysia, with an annual average power density of 24.54 W/m^2 and a predicted monthly annual mean of 17.98 kW/m^2 [67]. By capitalizing on advancements in wind energy technologies and leveraging diverse harvesting devices, Malaysia can harness its wind resources efficiently, offering a sustainable and economically viable solution to contribute significantly to the nation's renewable energy portfolio.

Malaysia has made notable progress in its renewable energy transition, currently achieving 13.3 % of its installed energy capacity from renewable sources, with a strategic goal of 40 % by 2035 as outlined in the Malaysia Renewable Energy Roadmap (MyRER) [68]. Solar energy plays a pivotal role due to Malaysia's favorable equatorial climate, which provides abundant sunlight throughout the year. Wind energy, though less developed, also shows potential in coastal regions, while biomass, primarily from palm oil waste, is a key renewable source. Despite these advancements, Malaysia faces challenges in balancing technological adaptation, financial investments, and policy execution. To achieve its ambitious targets, Malaysia can look to successful energy transitions in countries like Germany and Denmark. Germany's Energiewende serves as a blueprint for large-scale energy transformation, where renewable energy accounted for 46 % of the country's electricity mix in 2021 [69]. Denmark, a leader in wind energy, generated over 50 % of its electricity from wind power in 2020 [70]. Brazil, too, demonstrates the feasibility of large-scale renewable energy deployment, with 87.6 % of its energy coming from renewables, predominantly from hydropower as reported by the International Energy Agency [71]. Malaysia's integration of diverse renewable energy sources and the development of robust infrastructure could mirror these successes by implementing a comprehensive policy framework, encouraging public and private sector partnerships, and focusing on innovation in energy storage and grid integration [72].

For instance, replacing coal-fired power with solar energy could substantially cut SO_2, NO_x, and particulate matter emissions, which are major contributors to air pollution. A study by the U.S Energy information Administration [73] suggests that each megawatt-hour (MWh) of coal power replaced by renewables can reduce CO_2 emissions by approximately 0.9 metric tons. Given Malaysia's energy consumption and the carbon intensity of coal, increasing renewable energy capacity could potentially mitigate a substantial amount of GHG. For instance, if Malaysia were to transition 20 % of its energy capacity from coal to renewables, this could equate to a reduction of approximately 26.4 million metric tons of CO_2 annually, based on an average coal-fired power plant emission factor of 0.9 tons CO_2 per MWh. This reduction aligns with the substantial decreases in air pollutants observed in countries like Germany, where the Energiewende has led to a 45 % reduction in SO_2 emissions since the early 2000s [69], and Denmark, which has significantly cut its air pollution levels through aggressive wind energy investments. By enhancing renewable energy infrastructure and policies, Malaysia has the potential to achieve comparable reductions in air pollution and GHG emissions, demonstrating the critical role of renewable energy in advancing global sustainability goals and improving environmental and public health outcomes.

In conclusion, Malaysia's renewable energy landscape is richly diverse, with solar, wind, wave, and biomass energies presenting viable alternatives for sustainable development as summarized in Table 4. The consistent solar radiation, coupled with the tropical climate, makes solar energy particularly well-suited for widespread application in the country. Its scalability, efficiency, and compatibility with Malaysia's climatic conditions position solar energy as a promising choice for meeting energy demands. Additionally, the exploration of wind energy technologies, including non-conventional approaches of wind turbines underscores the potential for efficient harnessing of wind resources. While the feasibility of wave and biomass energies contributes to the broader renewable energy spectrum, technological advancements and infrastructural development may be essential for their widespread application. Given Malaysia's ample sunlight and the advancements in solar technology, prioritizing solar energy initiatives stands as a prudent strategy for the nation's sustainable energy future.

Table 4. Potential energy density for renewable energy sources in Malaysia.

Energy Source	Energy Density	Reference
Solar	400 to 600 MJ/m^2	[62]
Wave	> 40 MW h/m	[59]
Wind	17.98 kW/m^2	[67]
Biomass	13 MJ/kg (Bio–Oil)	[64]

3.3 Carbon emissions control

In recent years, Malaysia has put numerous efforts to combat the problem of air pollution due to carbon emissions. One of the carbon emission control measures in Malaysia is increasing the power plant's efficiency by using high-efficiency low-emission (HELE) coal technology, such as supercritical and ultra-supercritical system. As compared to the conventional coal power plant, these advanced technologies involve less amount of coal consumption to generate same amount of energy which helps to minimize the carbon emissions [74]. A typical supercritical and ultra-supercritical plants generate less emissions than subcritical plants by about 15 to 30 % [75]. Examples of Malaysian supercritical and ultra-supercritical coal power plants in Malaysia are Tanjung Bin Energy power plant (Johor) and Tuanku Muhriz power station (Seremban) [76].

As part of the Twelfth Malaysia Plan (12MP), Malaysia aims for carbon neutrality by 2050, committing to a 45 % reduction in GHG emissions by 2030 in line with the Paris Agreement [77]. According to the National Energy Policy (NEP) 2022-2040, carbon capture utilization and storage (CCUS) technology has been identified as one of the key solutions for minimizing the industrial carbon emissions. Carbon Capture and Storage (CCS) and Carbon Capture, Utilization and Storage (CCUS) technologies in Malaysia are still in the development stage. Various Malaysian universities are already offering courses related to these topics to raise public awareness, including University of Technology Malaysia (UTM), Institute of Technology Petronas (UTP) and National University of Malaysia (UKM) (Jorat et al., 2018). In recent years, Malaysia has begun to adopt CCS in numerous local coal-fired power plants. In Perak, the TNB Janamanjung coal-fired power station has successfully captured 85 to 95 % of CO_2 (8.5 – 9.5 million tonne CO_2 per year) from the processed plant after applying the post-combustion CCS technology [78].

Further, Toshiba Energy Systems and Solutions Corporation began installing CCS technology at TNB's coal-fired power plants (e.g., Jimah East Power) in September 2023 as well as providing training and personnel development support to TNB's engineers regarding the delivery and operation of CCS equipment [79]. Additionally, TNB has also signed a Memorandum of Understanding (MoU) with Petronas aimed at exploring the use of CCS technology in the gas-fired power plants [80]. To date, Malaysia only utilizes CCS technology; government and related companies (e.g., Petronas) are developing technologies to utilize CO_2 onshore and convert it into usable products [81]. Petronas is currently constructing a mega CCS project in the Kasawari gas field off the coast of Sarawak, which is estimated to be completed in 2026, reducing CO_2 emissions by 3.3 tonnes per year [82].

Afforestation and reforestation are two effective strategics in minimizing the carbon emissions into the atmosphere via the process of carbon sequestration. Afforestation is the process of turning abandoned and degraded agricultural lands into forests, while deforestation is replanting trees on deforested lands [83]. Trees are the natural carbon capture and storage system in which the CO_2 could be effectively absorbed through photosynthesis and trapped in their biomass or the surrounding soil for a long period time [32]. Research published in the Nature Climate Change reported that the forests are capable of absorbing about 7.6 billion metric tons of CO_2 annually [84]. In June 2019, the Malaysian Palm Oil Council (MPOC) initiated the "1 Million Forest Trees Planting" program as part of the government's Greening Malaysia agenda to plant 100 million trees across the country [85]. To date, over 90,000 trees have been planted in an area destined for restoration because of overlogging and forest fires in 225 hectares. In 2016, UTM decided to develop a forest replanting project and herbal plants in the UTM Recreational Forest, allocating 10 hectares for an ecotourism campus with diverse species like Meranti and Tualang trees, bamboo, and herbaceous plants [86].

While focusing on transportation emissions, EVs have become a favourable solution due to their green attributes. As compared to the internal combustion engine cars, pure EVs can provide us a cleaner road and environment as they produce lower carbon footprint and other air pollutants such as particulate matter, NO_x and CO while running. In order to encourage Malaysian to use EVs, the government has provided various tax incentives to both producers and consumers. Budget 2024 outlines that our government will extend individual tax relief of up to RM2,500 for costs associated with EVs charging facilities (including home charging) for a period of four years, extend tax rebates for EVs rentals for two more years, as well as offer rebates up to RM2,400 for electric motorcycle buyers earning less than

RM120,000 per year [87,88]. Additionally, the government is planning to expand the number of public charging stations to enhance the adoption of EVs in Malaysia. The Malaysian government has set an ambitious target of deploying 10,000 electric vehicle charging stations by 2025, along with 9,000 AC chargers and 1,000 DC fast chargers and converting 38 % of its transport into EVs by 2040 [89].

4 Limitations and suggestions

In the pursuit of mitigating air pollution, an essential aspect involves acknowledging and understanding the limitations associated with existing strategies and methodologies. While considerable efforts have been directed towards curbing air pollution, certain constraints hinder the effectiveness of these initiatives. This subtopic delves into the limitations that researchers, policymakers and environmentalists encounter in their endeavours to combat air pollution. Additionally, it explores insightful suggestions and recommendations aimed at overcoming these challenges and enhancing the overall efficacy of measures designed to address the complexities of air quality management. Through a critical examination of these limitations and the proposed solutions, a more comprehensive and nuanced approach can be developed to navigate the intricate landscape of air pollution control.

4.1 Limitations of Renewable Energy in Malaysia

Malaysia has many renewable energy sources that can be developed such as solar, wind, biomass, hydro, geothermal and tidal wave. However, in 2022, coal was the primary source of power generation in Malaysia, producing 76.4 terawatt-hours. After that, natural gas was the nation's second-largest source of electricity, producing 68.4 terawatt hours of power in a single year [60]. As of 2018, renewable energy sources only produced 6% of the total electricity. The government’s target is for renewable energy sources to produce about 20 % of electricity by 2025 and 35 % by 2050, respectively. Therefore, Malaysia has seen a rise in the understanding of the necessity of switching to environmentally friendly and sustainable energy sources in recent years. With a booming economy and a populace that is growing at a rapid pace, the need for energy has expanded dramatically. Malaysia has been making more investments in renewable energy sources in order to meet this demand while resolving environmental concerns. This chapter examines Malaysia's present situation with regard to renewable energy, the difficulties encountered, and the prospects for a sustainable future.

4.1.1 Wind Energy

First of foremost, wind energy refers to conversion of wind movement via wind turbines into electrical energy. While wind energy is less established compared to solar, Malaysia has recognized its potential, especially in coastal regions with favourable wind conditions. Pilot wind projects have been initiated, showcasing the feasibility of harnessing wind power. Continued investments in wind energy infrastructure could further contribute to Malaysia's renewable energy goals. However, the wind speed in Malaysia is relatively low with an average speed between 1.5 and 4.5 m/s. Higher altitude areas can harness between 9 to 11 m/s of wind power [37]. Variability in wind patterns and intermittency of wind resources are common challenges that need to be addressed to ensure a stable and reliable energy supply. Besides, Malaysia lacks the local researcher and company to design a Malaysia’s’ suitable proposal and wind turbines which leads to increase in capital cost including import fee. Therefore, absence of wind power technology and low wind speeds impact the viability and broader use of wind power.

4.1.2 Hydropower

Next, an important part of Malaysia's renewable energy profile is hydropower which helps Malaysia diversify its energy sources and minimize its reliance on fossil fuels. Hydropower refers to conversion of energy obtained from rainwater into electricity. Sarawak, one of the states in Malaysia, plays a crucial role in hydropower development. The state is rich in hydroelectric potential, and the government has been actively promoting hydropower projects to meet increasing energy demands. Sarawak Energy, the state's energy corporation, has been spearheading initiatives to harness the hydropower potential in the region. The construction of large dams can lead to environmental concerns such as habitat disruption, alteration of river ecosystems, affect water flow quality and displacement of communities. Balancing the economic advantages of hydropower with environmental and social considerations requires careful planning, stakeholder engagement and thorough environmental impact assessments. Therefore, a small hydropower plant has been suggested to minimize the destruction in ecosystems and also more reliable to every state. However, there is still a problem that capital cost was a bit lesser than big scale hydropower plant, but the returning was slow compared to big scale hydropower plant.

4.1.3 Solar Energy

Solar energy is a particularly rising and promising renewable resource in Malaysia due to its equatorial location resulting in abundant sunlight throughout the year. The 50 MW Solar plant is made up of 238,140 solar panels, generating more than 110,000 MWh of energy and averts 76,000 tons of CO_2 equivalent emissions per year. The government has implemented various initiatives to promote solar energy adoption, including the introduction of the Net Energy Metering (NEM) scheme and large-scale solar projects. The NEM scheme, introduced to encourage solar panel installation on rooftops, allows consumers to sell excess solar energy back to the grid. Additionally, the Large-Scale Solar (LSS) program aims to increase the capacity of solar power plants. These efforts have led to a significant increase in solar capacity, contributing to a more sustainable and diversified energy portfolio. Although solar energy has great potential, there are a number of obstacles and factors to take into account before solar energy is widely used in Malaysia.

The intermittent nature of solar power generation presents a significant issue because it is largely dependent on the availability of sunshine. As a result, weather patterns and the day-night cycle can cause fluctuations in energy production. The nation's tropical environment is good for exposure to the sun, but it also occasionally brings clouds which reduces the dependability of solar power. Furthermore, the extensive installation of solar panels necessitates a significant amount of land or space which may interfere with other land-use objectives like urban expansion or agriculture. Regardless several government incentives, the high upfront costs of building solar infrastructure remain a barrier to access especially for smaller-scale consumers. To solve the periodicity problem, effective energy storage methods are essential. In addition, breakthroughs in grid management and infrastructural modifications are needed to maintain stability while integrating solar electricity into current systems. The environmental impact of solar panel manufacturing, maintenance and disposal is also a source of concern involving the implementation of sustainable practices and recycling programs. Adoption of solar energy is more effective when it is accompanied by solid policies that foster investor confidence and industry stability.

Moreover, Malaysia lacks local suppliers to install and maintain solar PV systems. This will lead to high initial capital including importation fee and installation fee and maintenance fee (technician from other purchased countries). TS Solartech/ Solarvest was first local solar technology company which made its first production line in 2012. In order to promote broad adoption and overcome these obstacles, public education and understanding of the advantages, incentives and feasibility of solar energy are still crucial [90]. The cost dynamics of solar technology in Malaysia are further complicated by the state of the world economy which affects raw material costs and the dynamics of international trade. Addressing these multifaceted limitations requires a coordinated effort from policymakers, industry stakeholders, and the public to ensure the sustainable growth of solar energy in the Malaysian energy landscape.

4.1.4 Biomass

Biomass is renewable organic material that comes from plants and animals. It can be used to generate energy via burning process of agricultural crops, biogenic materials, animal manure and human sewage [91]. Besides, biomass has been reported as the fourth largest available energy resource of the world. Biomass is considered a carbon-neutral or low-carbon energy source because the CO_2 released during combustion is roughly equal to the amount absorbed by the plants during their growth. However, sustainable practices and proper management of biomass resources are essential to ensure environmental benefits and prevent negative impacts on ecosystems.

The logical connection between biomass energy production and consumption is driven by conventional market supply and demand with a price acting as a bidirectional mediator. There is scarcity when the price of biomass energy is too low because demand outweighs supply. As a result, producers step up their efforts to limit supply in order to boost demand which drives up prices. On the other hand, there is an excess supply compared to demand when prices are excessively high. In this instance, consumers either purchase less biomass energy or switch to more reasonably priced energy options. The suppliers lower their pricing to make up for the excess production, which increases the demand for biomass energy. If the connected production and consumption of biomass energy show a long-term relationship, then biomass energy is sustainable [91].

Malaysia has abundant biomass resources which are palm oil residual (oil palm fronds, empty fruit bunches (EFB), palm kernel shells (PKS) and palm oil mill effluent (POME)), wood residues, rice husk, sugar industry residues (sugarcane bagasse, molasses, press mud and others), municipal solid waste (MSW), rubber wood residues and coconut biomass. While biomass energy has gained popularity in Malaysia, there are several limitations and factors that should be addressed. The varied nature of biomass resources creates logistical issues for transportation, storage, and processing. Biomass reserves are spread, usually in rural areas, require efficient collection and transportation infrastructure. Other than that, handling a sustainable supply chain while preventing deforestation or environmental degradation from biomass extraction remains an important priority. Biomass projects must consider the possible conflict between biomass use for energy and other industries, such as agriculture or raw materials. Moreover, the economic viability of biomass projects may be altered by fluctuations in biomass prices and the availability of competing energy sources. Efficient and environmentally appropriate waste management techniques are required to avoid potential pollution from the disposal of biomass byproducts. Ongoing research and development activities aim to improve the efficiency of biomass conversion systems, although technological breakthroughs are required to address some operational problems. A comprehensive approach that incorporates technological innovation, sustainable sourcing methods, and regulatory frameworks is critical in Malaysia for realizing the full potential of biomass energy while reducing associated environmental and logistical restrictions.

Fig. 4 shows the global renewable energy production and consumption in the year 2021. China, United States and Brazil are the most leading producers and consumers in biomass as energy resources [91]. By referring to the policies from these top leading countries, some policies and suggestions can be considered when implementing biomass energy in order to increase the viability and coverage of biomass energy in Malaysia. In Brazil, most of the biomass energy obtained will use for biofuel production which can production of ethanol from sugarcane that used as a biofuel for transportation and flex-fuel vehicles that can run on ethanol or gasoline are common [92]. Besides, it is also used for biodiesel production from feedstocks such as soybean oil and animal fats. The biodiesel produced will be blended with conventional diesel to reduce dependence on fossil fuels. Brazil's implementation methods focus on cogeneration plants using bagasse, generating electricity for internal use and export [93].

Brazil's implementation methods focus on cogeneration plants using bagasse, generating electricity for internal use and export. Notably, the Proálcool Program promotes ethanol production from sugarcane, propelling Brazil to global leadership in sustainable biofuels. The government has introduced policies like feed-in tariffs and financial incentives to spur private sector investment in biomass power generation. These initiatives underscore Brazil's commitment to biomass energy as a central element in achieving climate goals, reducing carbon emissions, and ensuring energy security. Ongoing advancements and policy support position Brazil as a prominent player in the global transition to sustainable bioenergy. Brazil has established a robust framework for advancing its bioenergy sector, exemplified by initiatives such as the Proálcool Program, RenovaBio, biofuel blending mandates, and biomass power incentives. The Proálcool Program, launched in the 1970s, focuses on promoting the production and consumption of ethanol, primarily derived from sugarcane. This program has propelled Brazil to a global leader in sustainable biofuel production, with a notable emphasis on ethanol as a renewable transportation fuel. RenovaBio, introduced in 2017, further enhances the nation's commitment to decarbonizing its transportation sector. It sets ambitious targets for reducing GHG emissions, fostering the production of biofuels, and incentivizing cleaner fuel alternatives. The mandate for biofuel blending mandates a certain percentage of ethanol in gasoline and biodiesel in diesel, ensuring a steady market for biofuels and driving the transition towards renewable alternatives.

Simultaneously, Brazil encourages biomass power generation through incentives, including feed-in tariffs and financial support, promoting the utilization of organic residues for electricity production. These comprehensive policies underscore Brazil's dedication to a sustainable energy future, encompassing both the transportation and power sectors [94].

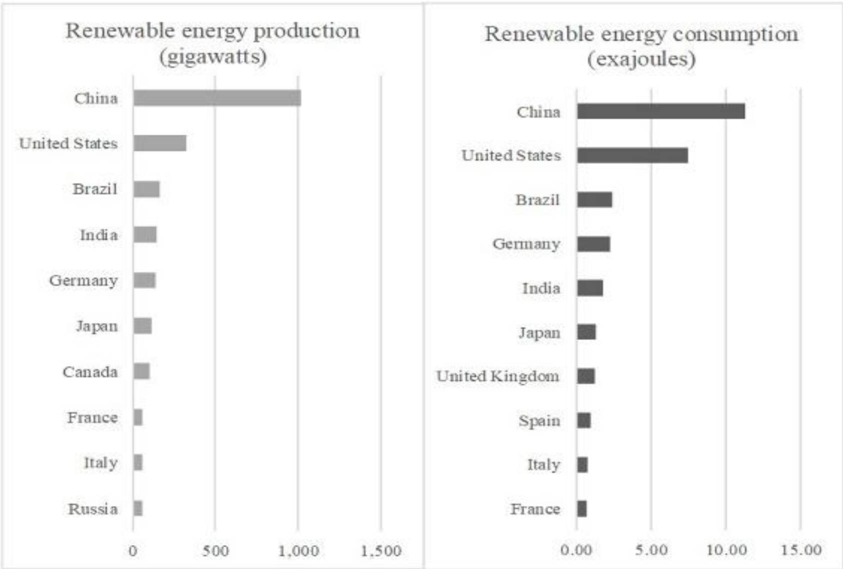

Fig. 4. Global renewable energy production and consumption in the year 2021 [91].

4.2 Suggestions to Tackle Urban Air Pollution

There are three main types of air pollution in Malaysia which are (i) haze from weather and forest fires in neighbouring Indonesia, (ii) pollution from industrial activity and (iii) air pollution from mobile emission sources like motor vehicles, mostly in urban areas. Following the increase of the population and the capability of locals to own motor vehicles, emission from motor vehicles has been on the rise, especially in urban areas. Government initiatives and policies are crucial in playing a part in the attempt to reduce urban air pollution.

4.2.1 Reducing Number of Registered Vehicles

According to the report in New Straits Time, the number of vehicles in the country has overtaken the human population, with an increase of at least a million vehicles annually since 2019 [95]. Compared to the human population that only stood at 32.6 million, there were 33.3 million registered vehicles including 47.3 % of cars, 46.6 % of motorcycles, 4.7 % goods vehicles (lorries etc.) and 1.1 % of buses and others [96]. Therefore, by controlling the carbon emissions by automobile, the air pollution in this country can be reduced and air quality can be improved. Fig. 5 indicated the number of new registered vehicles in Malaysia from 1988 to 2023. From the graph, the number of new registered vehicles increased obviously and dropped sharply in the years of 2020 and 2021.

A typical passenger vehicle will release around 4.6 metric tons of CO_2 per year under the assumption of driving distance of 18508 km (11500 miles) with average fuel consumption is 9.5 km per litre (22.2 miles per gallon) and 8,887 grams of CO_2 is released for each 3.8 litres (1 gallon) of fuel burned [98]. A study was conducted by European Environmental Agency in year 2022 to compare the average exact CO_2 emissions by different car manufactures and its specific CO_2 emission targets as shown in Fig. 6. The specific target was reset annually based on the average mass of the manufacturer's or pool's new vehicle fleet in a given year and aimed as a pool to compete between each car manufacturers. The CO_2 Emissions by transportation and in total amount are illustrated from year 1970 to 2020 in Fig. 7. As the year increased, the CO_2 emissions by transportation was increased along with the total amount of CO_2 emission in Malaysia. The CO_2 emission by transportation was contributed around 20 to 30 % since year 1970. Therefore, by reducing the number of vehicles on the road, the percentage that was occupied will be lower down obviously and also reducing to others GHGs.

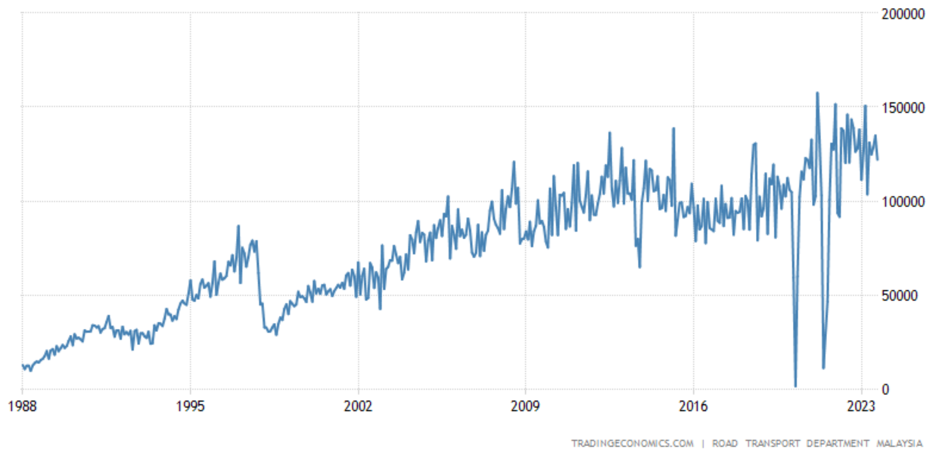

Fig. 5. The overview of new registered vehicles in Malaysia from 1988 to 2023 [97].

Public transportation systems are one of the solutions in reduction of demand of private vehicles. It promotes sustainable and well-balanced regional development, reduces adverse environmental impacts and improves road safety. Public transport also boosts the accessibility of basic services and the mobility of population groups. Professor Dr Kulanthayan K.C. Mani from Universiti Putra Malaysia (UPM) who is also the Global Alliance of NGOs for Road Safety board of directors' chairman suggested that the government should be emphasized the development of public transportation especially rail-based transportation system. Compared to road-based transportation, rail-based transportation is safer since it can help in relieves people of the stress of driving, eliminate the timeline concerns, promotes productivity throughout the journey as well as resolve the congestion nowadays.

By referring to our neighbour country, which is Singapore, its road networks are mainly completed via Mass Rapid Transit (MRT) and the Light Rail Transit (LRT), which cover the length and width of Singapore and serve a few neighbourhoods respectively. Furthermore, the ferries are chosen to link between mainland and islands. The completeness of the public transportation system can reduce and control the number of private vehicles in order to diminish the GHG emissions by the automobile. There are up to 5,800 buses in Singapore reported on May 2022 which maximizes the five criteria: availability, affordability, efficiency, convenience and sustainability that used for ranking a public transportation in specific countries [101]. Same with another Asian country, Japan, public transportation system in Japan including its Shinkansen (bullet trains), subways and buses, is known for its punctuality, cleanliness and extensive coverage. Tokyo's metro system, in particular, is one of the busiest and most comprehensive in the world.

Unfortunately, the biggest issue with Malaysia's public transportation is a lack of coverage and accessibility due to lack of proper connectivity [102]. As the most public transportation in Malaysia, current bus service usually cannot meet the demand of publics. The frequency of buses is low in some regions, especially rural regions which leads to long waiting times. Sometimes, the buses are not punctual. It has a bad tendency of not being very timely, therefore plaguing our commute with delays. Other than that, the bus stops and train or railway are too far away from people's houses for them to be conveniently accessible unless the people drive [103]. Besides, inadequate infrastructure development funding has slowed down the expansion and improvement of public transportation networks throughout the country. As a result, the coverage and connectivity are limited, especially in rural regions. Current infrastructure such as roads, railways, and bus terminals, frequently fail to fulfil the growing population's expectations. This leads to congestion, delays and overcrowding, making commuting a frustrating experience for the public [104].

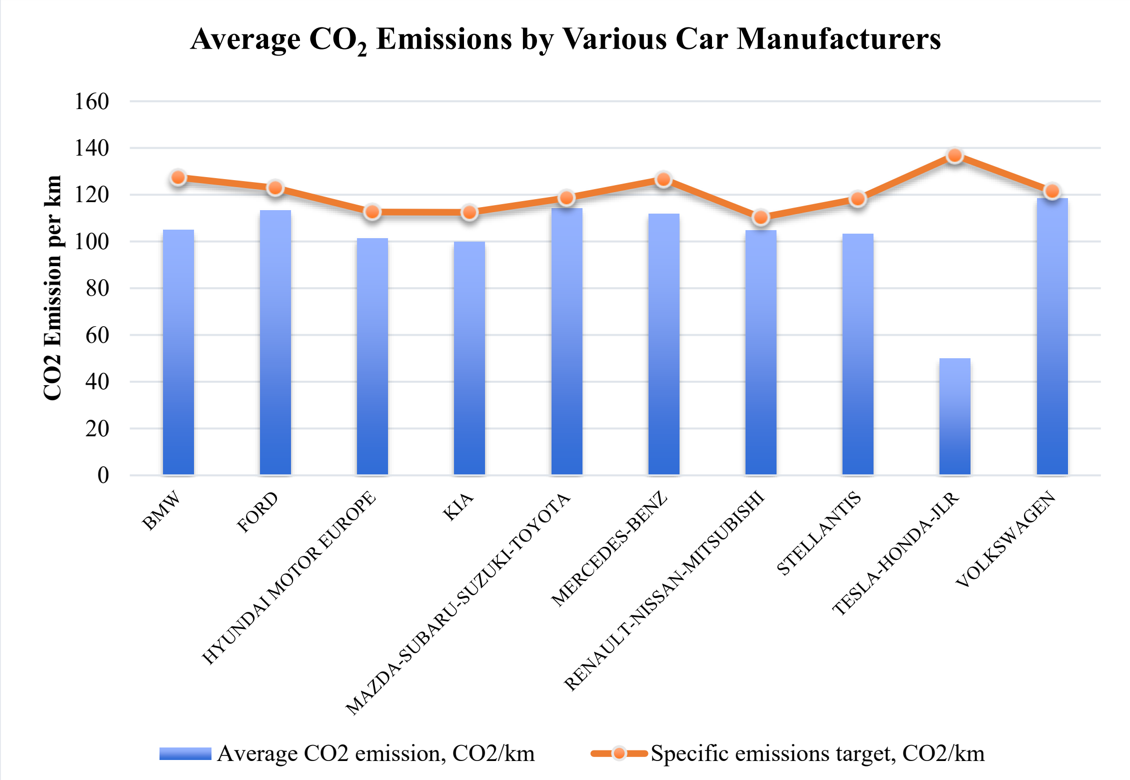

Fig. 6. Average CO_2 emissions and its target specific CO_2 emissions by various car manufacturers [99].

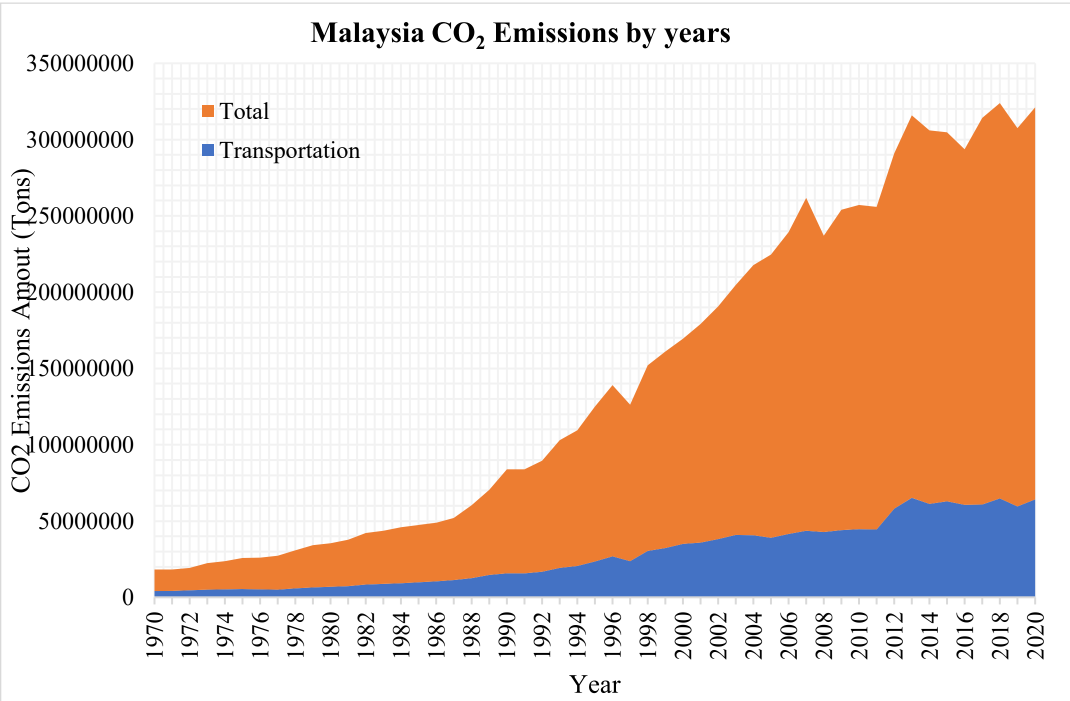

Fig. 7. Total CO_2 Emissions and transportation CO_2 Emissions by Year (tons) [100].

Besides than, in order to limit and control the number of vehicles, Singapore government had introduced Vehicle Quota System (VQS) ownership market-based license auctions since 1990. As a result, private vehicles are excessively expensive, and Singapore is well known for having the most expensive car ownership costs in the world. In addition, all cars in Singapore would be subjected to the

Additional Registration Fee (ARF). The ARF is a form of tax imposed on all cars during registration. The ARF is calculated based on the open market value (OMV) of the vehicle [105]. Fig. 8 shows the method of calculated ARF of a car and Fig.9 demonstrates the calculation of ARF (SGD 75337) for a Mercedes E200 that has open market value (OMV) of SGD 54388. These expensive charge on owning a private vehicle was successfully limited and decreased the number of new cars registered, increased awareness and willingness to take public transport, ensure the safety and well-being of public, reduced the emissions of GHG and other benefits.

Vehicle OMV	ARF Payable (%)
First $20,000	100% of OMV
Next $20,000 (i.e. between $20,001 to $40,000)	140% of OMV
Next $20,000 (i.e. between $40,001 to $60,000)	190% of OMV
Next $20,000 (i.e. between $60,001 to $80,000)	250% of OMV
$80,001 and above	320% of OMV

Fig. 8. Calculation additional registration fee (ARF) [105].

Mercedes E200	ARF Payable
First $20,000	$20,000
Next $20,000	$28,000
Next $14,388	$27,337
Total	**$75,337**

Fig. 9. Example calculation additional registration fee (ARF) for a Mercedes E200 with OMV SGD [105].

4.2.2 Vehicle Age Limitation

In 2021, Arthur van Benthem, an Associate Professor of Business Economics and Public Policy at Wharton claimed that the old and aging vehicles are the main contributors to the air pollution compared to new vehicles. He suggested that an increment on the registration fee or extra charge should be implemented on the older vehicles in order to encourage the changing of new vehicles [106]. The common problems of the old age vehicle are in terms of fuel efficiency. Older vehicles are generally less fuel-efficient than newer models. Lower fuel efficiency means higher fuel consumption and increased emissions per mile travelled. On the other hand, the new vehicles often feature more efficient and cleaner-burning engines. Technologies like direct fuel injection, turbocharging and hybrid or electric powertrains contribute to reduced emissions. This makes the new gasoline-powered vehicles have a much smaller CO_2 footprint or others GHG emissions than most of their older counterparts. The safety features of an old vehicle are concerning.

According to the 16th Meeting of The Malaysia-Singapore Joint Committee on The Environment Working Group in year 2018 [107], the GHG emissions limitation and standards for various vehicles ages were discussed which listed in Table 5. As conclude as below, the CO_2 emission standard was decrease significantly due to the new rule and regulation of European exhaust emissions. This represents that in order to meet the requirement of new standards, the new produced vehicles are designed accordance the implemented standards for each country. Therefore, due to the old technologies and designs, the old vehicles which usually failed to meet the latest emission standard compliance should be strictly control and scrapped when needed.

Table 5. CO_2 Emission Standard for motorcycles and motor vehicles under different vehicles ages in Malaysia and Singapore [107].

Registration Year of Vehicles	CO_2 Emission Standards (Vol%)	
	Motorcycles	Petrol motor vehicles
Malaysia		
Before 1 Jan 1997	-	4.5
After 1 Jan 1997	-	3.5
After 1 Jan 2004	4.5	-
Singapore		
Before 1 Oct 1986	6.0	6.0
On or after 1 oct 1986 but before	4.5	4.5
On or after 1 Jul 1992 but before 1 Jan 2001	-	3.5
On or after 1 Jan 2001 but before 1 Apr 2014	-	1.0
On or after 1 July 2003 but before 1 October 2014 and three-wheeled motorcycles	4.5	-
On or after 1 Apr 2014	3.0	0.5

In order to deal with issue, some countries have come out the related rules and regulations to limit the on-road vehicles' age. For example, in Singapore also, their government have strictly imposed a ten-year age limit on vehicles. Owning a Certificate of Entitlement (COE) is very important in their country in order to have their own private vehicles. COE is an allocate license for owning a vehicle in Singapore for ten-year period. COE system is cooperated with VQS, a landmark scheme implemented to regulate the growth of the vehicle population in Singapore, which is among the densest in the world [108]. Through this method, several objectives can be achieved: (i) ensure the safety of road users; (ii) control the number of registered vehicles; (iii) minimize the negative impact due to old age car such as inefficiency combustion; and (iv) improve the air quality.

There are approximately 19 million (58 %) of 10 years old or above out of 33 million registered vehicles in Malaysia [109]. Unfortunately, Malaysia does not have a specific nationwide age limit for private vehicles. Vehicle regulations in Malaysia primarily focus on roadworthiness and safety rather than the age of the vehicle. However, vehicles in Malaysia are required to undergo periodic inspections to ensure they meet safety and emissions standards. For private cars, the periodic inspection is known as the "PUSPAKOM inspection" or "vehicle inspection," and it is typically required every one or two years, depending on the age of the vehicle. The inspection is designed to assess the overall condition, safety features, and emissions of the vehicle [110].

5 Conclusion

In a nutshell, air pollution is one of the greatest environmental concerns in every country. In Malaysia, air pollution primarily results from various anthropogenic activities and population growth, leading to increased energy demand. Over the last few decades, the Malaysian government has invested a great deal of time and effort into minimizing the air pollution issue to protect the environment and public health. Such strategies include transitioning to renewable energy sources, enacting stringent laws and regulations, and implementing carbon emission controls. However, addressing these challenges is complex and requires ongoing, sustained collaborative actions, technological advancements, and adaptive strategies.

The efforts to reduce air pollution in Malaysia align closely with several Sustainable Development Goals (SDGs), including SDG 7 (Affordable and Clean Energy), SDG 13 (Climate Action), and SDG 3 (Good Health and Well-being). By shifting from fossil fuels to cleaner energy sources such as solar, wind, and biomass, Malaysia is advancing towards SDG 7's objective of ensuring sustainable and reliable energy for all. These initiatives are also crucial for reducing GHG emissions, contributing to SDG 13's aim of combating climate change. Moreover, reducing air pollution supports SDG 3 by improving public health and well-being, as lower pollution levels can decrease the incidence of respiratory and other pollution-related diseases [111].

Malaysia's transition to renewable energy and stringent carbon controls not only further national sustainability goals but also play a significant role in fulfilling international climate commitments, such as those outlined in the Paris Agreement. By working towards reducing emissions and expanding renewable energy capacity, Malaysia is making substantial contributions to the global effort to limit temperature rise and transition to a low-carbon future. Collaborative efforts with other countries and adherence to global agreements are essential for maximizing the impact of these actions, ensuring that Malaysia's efforts are aligned with and contribute to the global agenda for a sustainable and healthy future.

Declaration of Conflict of Interest

The authors declared that there is no conflict of interest with any other party on the publication of the current work.

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