Review of Decadal Changes in ASEAN Emissions Based on Regional and Global Emission Inventory Datasets

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ABSTRACT

In Asia, anthropogenic emissions have increased substantially over the last decade from various sectors, including power generation (PG), industries, road transportation (RT), and residential. This study analyzed different regional (REAS, MIX-Asia) and global (EDGAR) emission inventory (EI) datasets to provide insight into ASEAN’s comprehensive emission status (emission trend, sectoral and country-specific emissions, changes in spatial distribution) during 2000–2015. The study observed a considerable increase in SO2, NOx, CO, CO2, and particulate matter (PM) emissions in ASEAN during this period. Results analyzed from the EDGAR EI dataset (2015) show that among the pollutants, SO2, CO2, and N2O were substantially contributed by the PG sector (43.4–56%), while CO, NOx, NMVOC, and CH4 were from the RT sector (35.6–61.5%), and PM and NH3 emissions were from the residential sector (50–80.6%). Similar contributions were also observed in 2000 and 2010. It is apparent that these sectors contributed noticeably to the total Asian emission (i.e., 14–34% in 2010, based on the MIX-Asian dataset). We have observed increasing annual emission trends for most pollutants in ASEAN countries, with more significant emission growth in Vietnam (e.g., SO2 and NOx emissions increased by 232% and 145%, respectively). Considerable changes in spatial emission distributions over the ASEAN between that period were also observed caused by the shifting of sparse development into concentrated urban expansion surrounding large metropolitan clusters. The information from this study will be vital for the ASEAN governments to review and update their approved/planned regulations on emission control with prioritizing the sectors aimed at air quality management and environmental sustainability.

Keywords: Southeast Asia, Emission inventory, Industry, Thermal power plants, Road transportation

1 INTRODUCTION

Developing anthropogenic emission inventory (EI) in a large geographic region like Asia is crucial for numerous atmospheric and climate research. Over the last decade, some efforts have been made to develop Asian EI (Kurokawa et al., 2013; Li et al., 2017; Ohara et al., 2007; Streets et al., 2003; Zhang et al., 2009) following either bottom-up or top-down approach or a combination of both. In the large Asian region, Southeast Asia (SEA) has undergone robust economic growth in the last few decades (Chifflet et al., 2018; Engels et al., 2018; Richter et al., 2005). Since 2000, the economy has been growing sharply, with an average of 5.2% annually (Koplitz et al., 2017), resulting in a significant increase in energy demand and consumption in multiple sectors, including road transportation (RT), power generation (PG), industry, and residential. It consequently leads to high emissions of short-lived climate pollutants (SLCP) and greenhouse gases (GHG) as fossil
fuels are typically used as the primary energy source in these sectors. In general, coal is used as the dominant fossil fuel in thermal power plants (TPPs) to boost electricity generation and meet growing electricity demand in SEA (Fuentes and Chapman, 2021; Roy et al., 2021a). The burning of coal significantly increased the regional emissions in the past decades, and is expected to continue contributing to a large portion of overall emissions (Lawrence and Lelieveld, 2010; Ohara et al., 2007). The International Energy Agency (IEA) projected that by 2035, energy demand in SEA would be 83% higher than in 2011 (IEA, 2013), and coal will remain the principal energy source to meet that growing demand, which would worsen air quality in the region (Lai et al., 2016).

In the Southeast Asian region, anthropogenic emission varies largely both temporally and spatially. The RT (e.g., motorcycle, bus, truck, personal cars) and industrial sector are the dominant emission sources of pollutants in urban areas (UNEP, 2017). In rural areas, biomass burning is the primary emission source, followed by the emissions from RT, as many people still rely on solid biomass for domestic purposes such as cooking, heating (Huy et al., 2021). Bang et al. (2018) asserted that air pollutants, including CO, SO\textsubscript{2}, NO\textsubscript{x}, VOCs, etc., are emitted from three primary sources (i.e., point, mobile, and area sources) in SEA. These pollutants also contribute to the formation of secondary pollutants such as particulate matter (PM) and ozone (O\textsubscript{3}) and create haze episodes. Different studies (e.g., Hopke et al., 2008; Kim Oanh et al., 2006) reported high PM\textsubscript{10}, PM\textsubscript{2.5}, BC, and OC in this region. High levels of these pollutants degrade the local air quality, influence the regional air quality through transboundary impact and, consequently, affect the global climate (Campbell-Lendrum and Prüss-Ustün, 2019; Huy et al., 2021; Kurokawa and Ohara, 2020; Soejachmoen, 2019). Hence, providing an insight into a comprehensive EI covering the significant anthropogenic emission sectors for the fast-growing Southeast Asian region is crucial.

Southeast Asian emission estimation during 2000–2015 has been covered partially by some regional (Kurokawa et al., 2013; Kurokawa and Ohara, 2020; Li et al., 2017; Ohara et al., 2007; Streets et al., 2003; Zhang et al., 2009) and global (e.g., EDGAR) (EC-JRC/PBL, 2019) EI works. Some national EIs have been developed mainly in Vietnam and Thailand, focusing on- RT, industries, and the PG sector (Huy and Kim Oanh, 2017; Pham et al., 2008; Roy et al., 2021a, 2021b). Permadi et al. (2018) developed the EI of PM and BC for multiple sectors in Indonesia, Thailand, and Cambodia in 2007. Huy et al. (2021) developed the EI for PM from the residential combustion in SEA. However, to the best of our knowledge, no effort has been made to provide a comprehensive scenario on available EIs on ASEAN (Association of Southeast Asian Nations) countries yet and address the discrepancies among the regional and global EIs covering ASEAN. As the future anthropogenic emission contribution from this rapidly growing economic region is anticipated to increase significantly to the global annual emissions (Roy et al., 2021a; Sandu et al., 2019), providing a comprehensive historic emission scenario for the ASEAN considering regional and global EI works could be crucial to understand better the regional emission trend, significant sources of emission growth, major contributing emission sectors, and its influence on total Asian anthropogenic emissions. We believe that the findings gained from our study will contribute considerably to the literature. It could provide local governments of ASEAN useful insights into policy decisions focusing on regional emission control and future air quality management to comply with the international agreement on GHG emission mitigation and climate action plan (e.g., COP21 and COP26).

Therefore, in view of the regional and global EI datasets, this study is aimed: (i) to investigate the anthropogenic emission trends during 2000–2015 in ASEAN; (ii) to identify the influential factors behind emission growth and changes, (iii) to analyze the sectoral emissions; and (iv) to illustrate the changes in the spatial emissions distribution. In this study, we select the 2000–2015 period to investigate the Southeast Asian EI, as during this period, significant changes in emissions have occurred in ASEAN. Besides, the updated emission data are available up to 2015 in the regional and global EI datasets. In this article, the schematic representation of the study has been provided in Section 2. Section 3 provides an overview of Southeast Asian emissions and the progress to develop and update EI in the Asian domain (including ASEAN). Section 4 includes emission trends, factors influencing emission changes, emission growth during 2000–2015, and a summary of EI results in ASEAN. Sectoral emission contribution has been presented in Section 5. Section 6 provides emission trends for each ASEAN country. Finally, the spatial changes in emissions have been illustrated in Section 7.
Fig. 1. Research framework for studying comprehensive emission status in ASEAN. Notes: Years in the bracket represent the base year of EI. *Considered as the base year 2000 from the EI results of the TRACE-P (2001) campaign, used for MICS-Asia II.

2 METHODOLOGY AND DATA

The methodology of the study focused on quantitative information regarding the total amount of emission generated for each SLCP (SO\textsubscript{2}, NO\textsubscript{x}, CO, NMVOC, PM\textsubscript{10}, PM\textsubscript{2.5}, BC, OC, and NH\textsubscript{3}) and GHG (CO\textsubscript{2}, CH\textsubscript{4}, N\textsubscript{2}O) during 2000–2015 from the ASEAN countries and the sector-specific (i.e., PG, RT, residential, and industrial) total emissions during that period. Please note that our study focuses on the member countries of ASEAN, hence emissions from East Timor were not considered. To analyze the proportion of emission growth, emission trend, country-specific emissions, and sectoral emissions in ASEAN countries, we extracted the emission data mainly from the regional EI datasets (e.g., MIX-Asia and REAS) and global EI dataset (EDGAR v5.0). The geographic distribution of pollutants in 2000 and 2015 were also analyzed using the annual emission grid maps provided by EDGAR v5.0 at 0.1° × 0.1° resolution over the SEA. The spatial emission maps were created using the NCAR Command Language (NCL) (http://www.ncl.ucar.edu/). Other necessary data, including the country-specific forest area, annual population, GDP per capita, sector-specific CO\textsubscript{2} emissions relevant from agricultural land use, energy, and land use, land-use change, and forestry (LULUCF), were extracted from the World Bank database (World Bank, 2021) and the Food and Agriculture Organization of the United Nations (FAO) database, i.e., FAOSTAT (FAOSTAT, 2021). Fig. 1 shows the research framework for studying comprehensive emission status in ASEAN.

3 SOUTHEAST ASIAN EMISSION STATUS AND EMISSION INVENTORY DEVELOPMENT- LITERATURE REVIEW

3.1 Overview of Southeast Asian Anthropogenic Emissions

Energy demand is growing drastically in SEA due to its fastest development in different sectors (e.g., industry, PG, RT). Fossil fuels have been used as the dominant energy source to meet the growing demands, leading to high SLCP and GHG emissions (IEA, 2021). Lee et al. (2018) asserted that PM discharge from anthropogenic activities and extensive biomass burning is highly responsible for air quality degradation in SEA. Lee et al. (2013) also reported the increasing emission trend in SEA from different anthropogenic sources. For instance, a drastic increase in CO\textsubscript{2} over the last
few years has been observed in most ASEAN countries (e.g., Thailand, Malaysia, Indonesia, and Vietnam). It is assumed that unprecedented growth in population, economic growth, and an increase in GDP per capita substantially influence the increased CO₂ emission, although population growth is not considered a direct factor for determining CO₂ emissions in the long-run (Sulaiman and Abdul-Rahim, 2018). Fig. 2 shows an example of the increasing trend of anthropogenic CO₂ emissions in Vietnam and Indonesia during 2000–2015 with the growth in GDP per capita and energy use per capita, analyzed from FAOSTAT (2021) and World Bank (2021). This study considered these factors, as it is reported that CO₂ emissions increase with economic growth and energy use (Sulaiman and Abdul-Rahim, 2018). Besides, vegetation and peat fires also result in considerable CO₂ and other air pollutants, consequently deteriorating this region's air quality in SEA (Page et al., 2002). For instance, Reddington et al. (2014) reported the substantial contribution of PM emissions (mainly PM₂.₅) to a large SEA region, resulting from vegetation and peat fires. Regarding the long-term impact (e.g., climate change) on the SEA region, emission contributions from fossil fuels and biomass burning are considered crucial in different studies (Koplitz et al., 2017; van der Werf et al., 2009; Wang, 2004). Wang (2004) noticed that the emissions of PM have generous impacts on the SEA climatic features such as variations in precipitation, temperature, and energy budgets.

SEA, with increased population, industrial development, and rising economy, the electricity demand has dramatically increased recently. Among the Southeast Asian countries, the four largest electricity consumers (i.e., Indonesia, Vietnam, Thailand, and Malaysia) account for over 80% of the total electricity demand in the region (IEA, 2020). Fossil fuels (mainly coal) are predominantly used to meet increased electricity demand (Fuentes and Chapman, 2021). According to IEA (2017), coal demand in SEA has been increased three-fold since 2000, whereas most of it is being used for thermal PG. As coal constitutes harmful substances, it emits SO₂, NOₓ, CO and leads to PM₂.₅ formation; hence, it contributes substantially to regional air quality degradation (Lam, 2018). Vadrevu et al. (2017) reported that coal accounts for 91% of the total energy use as a primary energy source, resulting in severe air pollution by emitting a massive amount of CO₂, sulfur, and PM. Kurokawa and Ohara (2020) also reported the increasing trend in annual emissions in SEA during 2000–2015.

3.1.1 Emission sources and categories

SLCP and GHG are emitted from various sources in the Southeast Asian region, as identified in different EI studies covering the ASEAN (Table S1 in Supplementary Material (SM)). In most EIs, emission sources have been categorized into three main types (i.e., point, mobile, and area sources). TPPs and industries (e.g., oil refineries, steel mills, metal, paper and pulp, cement, brick, and chemical industries) have been considered the principal point sources (Bang et al., 2018; Huy and
Kim Oanh, 2017; Kurokawa et al., 2013; Kurokawa and Ohara, 2020; Pham et al., 2008; Roy et al., 2021a; Vongmahadlek et al., 2009). For mobile sources (i.e., on-road and non-road transportation), most EIs have focused on on-road transportation sources, including motorcycles, light-duty vehicles, and heavy-duty vehicles (Bang et al., 2018; Ho and Clappier, 2011; Huy et al., 2020; Kurokawa et al., 2013; Roy et al., 2021b; Trang et al., 2015; Vongmahadlek et al., 2009). However, only a few studies (Bang et al., 2018; Vongmahadlek et al., 2009) incorporate non-road (e.g., air traffic, pier) transportation sources. Regarding the area sources, agricultural open burning, biomass burning, and rice straw burning have been considered the dominant emissions sources (Bang et al., 2018; Kurokawa and Ohara, 2020; Vongmahadlek et al., 2009). All these sources contribute considerably to the total annual emissions in SEA, which will be presented in the following sections.

3.2 Development in EI Covering Asian Domain

3.2.1 Regional EI datasets

Kato and Akimoto (1992) developed the initial EI for East, Southeast, and South Asia, followed by other EI works in the Asian domain (Akimoto and Narita, 1994; EC-JRC/PBL, 2019; Kurokawa et al., 2013; Ohara et al., 2007; Streets et al., 2003; Zhang et al., 2009). Table 1 summarizes development in EIs in the Asian domain. It is apparent that a few efforts have been made to estimate historical emissions from Asian countries and estimate future emissions. Anthropogenic emissions from Asian countries significantly influence global emission concentrations (Cofala et al., 2007; Saikawa et al., 2017; Schwela et al., 2006). Hence, Ohara et al. (2007) developed the Regional Emission Inventory Asia (REAS) v1.1 to establish historical and future emissions, including multiple emission species. Energy consumption in different sectors has increased significantly in Asian countries since 2003 (IEA, 2017), resulting in considerable growth in emission trends. Moreover, the local activity data and emission species of REAS v1.1 have become outdated after 2000 (EI base year). Therefore, it was vital to update the REAS with higher temporal and spatial resolution, include more emission species, and expand regional coverage. Saikawa et al. (2017) stated that an accurate and updated EI is indispensable for Asia as most countries have the worst situation in terms of air pollution. Considering these factors, the REAS v1.1 has been updated to REAS v2.1 by Kurokawa et al. (2013), with significant areas of improvement. REAS has been further updated by Kurokawa and Ohara (2020) by developing a long-term historical EI (1950–2015) for multiple pollutants (Table 1).

Like REAS, MIX-Asia is a newly developed EI, focusing on the Asian region (including ASEAN) to support the Model Inter-Comparison Study for Asia Phase III (MICS-Asia III). It should be mentioned that the MICS-Asia (phase I) was one of the initial efforts (initiated in 1998) to study the long-range transport of pollutant (sulfur) within the Asian region, mainly in China. The extension phase of MICS-Asia (i.e., MICS-Asia II) includes an additional feature (i.e., global inflow of pollutants to Asia), and the study domain extended to cover SEA (Carmichael et al., 2008; Chen et al., 2019; Gao et al., 2018; Hayami et al., 2008; Li et al., 2017). It should be noted that TRACE-P (Transport and Chemical Evolution over the Pacific) emission datasets developed by Streets et al. (2003) have been used for the MICS-Asia phase II (Kannari et al., 2008; Li et al., 2017).

3.2.2 Global EI datasets

Rising anthropogenic emission has become one of the main concerns worldwide. Hence, efforts have been made to identify the key emission sources to develop and update existing Global EIs. It helps adopt new policies or reform existing systems as the emission reduction strategy. Crippa et al. (2018) identified several global EIs developed recently. Examples of these EIs include "Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS), MACCity by Granier et al. (2011), Klimont et al. (2013) for SO₂, ECLIPSE v5a by Klimont et al. (2017) for PM, the Hemispheric Transport of Air Pollution Inventory (HTAP v2.2) by Janssens-Maenhout et al. (2015), the Community Emission Data System (CEDS) by Hoey et al. (2018)". However, in this study, the Emission Database for Global Atmospheric Research (EDGAR) v5.0 has been used for emission estimation, analyzing emission growth, and emission comparison with available EIs (presented in the following sections), as it has been widely used in most of the global, regional or local EI studies worldwide. In the Asian region, the EDGAR dataset has been extensively used to compare the
### Table 1. Summary of development in Asian EIs covering Southeast Asia/ASEAN.

<table>
<thead>
<tr>
<th>EI/Database</th>
<th>Inventory year</th>
<th>Emission sources/sectors</th>
<th>Spatial resolution</th>
<th>Area coverage</th>
<th>Emission species</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDGAR v5.0</td>
<td>1970–2015</td>
<td>Industrial processes, energy uses, on-road and off-road</td>
<td>0.1° × 0.1°</td>
<td>Global</td>
<td>BC, OC, CO, SO(_2), NO(_x), NH(_3), CO(_2), CH(_4), NO(_x)</td>
<td>EC, JRC/PBL, 2019</td>
</tr>
<tr>
<td>Streets et al. (2000)</td>
<td>2000</td>
<td>Transportation, agriculture, other anthropogenic sources, coal, and others</td>
<td>1° × 1° to 30 s × 30 s (0.7 km × 0.7 km)</td>
<td>EA, SEA, and SA</td>
<td>SO(_2), NO(_x), CO(_2), CO(_2)</td>
<td>Streets et al., 2003; Zhang et al., 2006</td>
</tr>
<tr>
<td>REAS v1.1</td>
<td>2000</td>
<td>Combustion (fossil fuel, biofuel), non-combustion (industrial processes, oil, solvent, etc.), agriculture and transportation</td>
<td>0.5° × 0.5°</td>
<td>EA, SEA, and SA</td>
<td>SO(_2), NO(<em>x), CO(<em>2), BC, OC, VOC, PM(</em>{10}), PM(</em>{2.5}), BC, OC</td>
<td>Streets et al., 2003; Zhang et al., 2006</td>
</tr>
<tr>
<td>The Center for Global and Regional Environmental Research (CGGER)</td>
<td>2000–2006</td>
<td>Power, industry, residential, and transportation</td>
<td>0.25° × 0.25°</td>
<td>EA, SEA, and SA</td>
<td>SO(_2), NO(<em>x), CO(<em>2), VOC, PM(</em>{10}), PM(</em>{2.5}), BC, OC</td>
<td>Streets et al., 2003; Zhang et al., 2006</td>
</tr>
<tr>
<td>REAS v2.1</td>
<td>2000–2008</td>
<td>Fossil fuel and biofuel combustion in TPPs, industry, other transport, and agriculture</td>
<td>0.25° × 0.25°</td>
<td>EA, SEA, and SA</td>
<td>SO(<em>2), CO(<em>2), NMVOC, CH(<em>4), NH(<em>3), PM(</em>{10}), PM(</em>{2.5}), BC, OC, VOC, PM(</em>{10}), PM(</em>{2.5}), BC, OC</td>
<td>Streets et al., 2003; Zhang et al., 2006</td>
</tr>
<tr>
<td>REAS v3</td>
<td>1990–2015</td>
<td>TPPs, industrial agricultural sector, industrial processes, energy uses, on-road and off-road</td>
<td>0.25° × 0.25°</td>
<td>EA, SEA, and SA</td>
<td>SO(_2), NO(<em>x), CO(<em>2), NMVOC, CH(<em>4), NH(<em>3), PM(</em>{10}), PM(</em>{2.5}), BC, OC, VOC, PM(</em>{10}), PM(</em>{2.5}), BC, OC</td>
<td>Streets et al., 2003; Zhang et al., 2006</td>
</tr>
<tr>
<td>Zhang et al. (2006)</td>
<td>2006</td>
<td>TPPs, residential, transportation</td>
<td>0.25° × 0.25°</td>
<td>EA, SEA, and SA</td>
<td>SO(_2), NO(<em>x), CO(<em>2), NMVOC, CH(<em>4), NH(<em>3), PM(</em>{10}), PM(</em>{2.5}), BC, OC, VOC, PM(</em>{10}), PM(</em>{2.5}), BC, OC</td>
<td>Streets et al., 2003; Zhang et al., 2006</td>
</tr>
<tr>
<td>MIX-Asian EI</td>
<td>2008, 2010</td>
<td>Energy, industry, solve, use, agriculture and transportation</td>
<td>0.25° × 0.25°</td>
<td>EA, SEA, and SA</td>
<td>SO(_2), NO(<em>x), CO(<em>2), NMVOC, CH(<em>4), NH(<em>3), PM(</em>{10}), PM(</em>{2.5}), BC, OC, VOC, PM(</em>{10}), PM(</em>{2.5}), BC, OC</td>
<td>Streets et al., 2003; Zhang et al., 2006</td>
</tr>
<tr>
<td>ECLIPSE V5a</td>
<td>2010, 2015</td>
<td>Energy, industry, solve, use, agriculture and transportation</td>
<td>0.25° × 0.25°</td>
<td>EA, SEA, and SA</td>
<td>SO(_2), NO(<em>x), CO(<em>2), NMVOC, CH(<em>4), NH(<em>3), PM(</em>{10}), PM(</em>{2.5}), BC, OC, VOC, PM(</em>{10}), PM(</em>{2.5}), BC, OC</td>
<td>Streets et al., 2003; Zhang et al., 2006</td>
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<tr>
<td>Notes: – Not available, EA, East Asia, SEA, Southeast Asia, SA, South Asia, TPPs, Thermal power plants.</td>
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estimated emissions from anthropogenic sources in many EI studies (e.g., Huy and Kim Oanh, 2017; Kurokawa et al., 2013; Ohara et al., 2007; Permadi et al., 2018; Saikawa et al., 2017; Vongmahadlek et al., 2009). The EDGAR database has been developed based on the top-down and bottom-up approaches that provide historical emission data (SLCP and GHG) and grid maps for the individual countries during 1970–2015, allowing the comparison among the nations.

**4 EMISSION TREND AND FACTORS INFLUENCING EMISSION CHANGES (2000–2015)**

The emissions were changing drastically in the Southeast Asian region due to the influence of several factors, including industrial development and economic growth, increased traffic, PG and heating, and biomass burning activities (Kurokawa et al., 2013; Lasko et al., 2018; Ohara et al., 2007; Schwela et al., 2006; Streets et al., 2003). For instance, the study showed an increasing trend of anthropogenic emissions of different SLCP (SO$_2$, NO$_x$, CO, NMVOC, PM$_{10}$, PM$_{2.5}$, BC, OC, and NH$_3$) and GHG (CO$_2$, CH$_4$, N$_2$O) in ASEAN during 2000–2015 (Fig. 3), analyzed from EDGAR v5.0 (EC-JRC/PBL, 2019). We believe that the new EDGAR dataset (i.e., EDGAR v5.0) can represent well the ASEAN anthropogenic emission trend, as it includes historic emission (1970–2015) estimates, considering region-specific emission factors relevant to the emission sectors, emission control measures, and required activity data from recent available scientific literature and reports. Besides, it was crucial to use the EDGAR dataset as we intended to provide the decadal changes in ASEAN emissions whereas most of the global emission inventories do not cover all pollutants (including GHG) and historic time series for anthropogenic emissions. Additionally, quality control and quality assurance procedures have been used to evaluate the EDGAR dataset for emission time series as well as grid maps (Crippa et al., 2018). Among the pollutants, a substantial increase in SO$_2$, NO$_x$, CO, CO$_2$, and PM emissions was observed after 2010, mainly due to the significant growth in fossil fuel-fired TPPs in this region to meet the growing electricity demand in various sectors and because of the increased road vehicles. Lee et al. (2013) also reported a significantly increasing emission trend in the Southeast Asian region.

In the Southeast Asian region, changes in population growth and rapid urbanization are the important driving forces that lead to high emissions of pollutants. In 2000 and 2015, around 45% and 52% Southeast Asian population lived in urban areas. The total population increased from 525–634 million during 2000–2015 (UN, 2019). As a result, the primary demand for food, housing,
Fig. 4. Factors influencing emission changes during 2000–2015 (Source: Analyzed from FAOSTAT, 2021; World Bank, 2021). Notes: * Total CO2 emission (in Tg) from LULUCF; † Energy use in 100 kg of oil equivalent per capita.

infrastructure, power and heating, transportation, etc., has increased considerably. These increased demands created enormous pressure on every sector, including natural forest lands and energy resources (e.g., fossil fuels). In most Southeast Asian countries, due to the rapid loss of natural forest lands through numerous human activities such as deforestation (illegal logging), agricultural expansion, and commercial cultivation, GHG emissions have increased considerably. This increased emission significantly impacted the regional and global climate system. The study shows that compared to other Asian regions (i.e., EA and SA), SEA (except Vietnam, where the net gain of the forest area was observed) had experienced a considerable loss in natural forest lands during 2000–2015 (Fig. S1 in SM). The study shows that forest area in Southeast Asian countries has declined considerably with the increased population. At the same time, CO2 emissions associated with different factors, including land-use changes and increased energy uses, increased significantly (Fig. 4), analyzed from FAOSTAT (2021) and World Bank (2021). For instance, the result shows that forest land dropped considerably between 2000 and 2015 (i.e., ~5%). During this period, CO2 emissions increased noticeably (i.e., ~5%) through the influence of various factors, including extensive agricultural activities to support the growing population, land-use changes, and increased emissions in the energy sector. This region’s per capita energy uses (fossil fuel consumption) increased by ~23% between 2000 and 2015 (Fig. 4).

4.1 Major Sources of Emission Growth between 2000–2015

This study analyzed the significant sources of emission growth for different pollutants in ASEAN between 2000–2015 using the EDGAR v5.0 (Fig. 5) EI database (EC-JRC/PBL, 2019). Results show that the PG and heating sector contributed the most substantial portion of SO2 and NOx emissions among the various sources. The emission growth rate was 67% and 39%, respectively, followed by manufacturing industries and construction activities (MIC) (24% and 33%). One possible reason is the increased fossil fuel consumption by rapidly growing TPPs and industries. A similar contribution was observed for CO2 emission, whereas PG and the heating sector contributed the most significant portion (49%), followed by RT and MIC activities. Roy et al. (2021a) reported significant contribution and growth of SO2, NOx, and CO2 emissions from the PG sector in Vietnam during 2010–2015. Huy and Kim Oanh (2017) also reported a similar finding for Vietnam in 2010. Pham et al. (2008) reported a significant contribution of SO2 and NOx emissions from the PG and industrial sectors in Thailand. In terms of NMVOC and CO emission, the highest contribution was from RT. The main reason was the fast growth in transport vehicles in ASEAN during that period, also reported by Kurokawa et al. (2013). A similar finding was reported by Roy et al. (2021b), with
Fig. 5. Significant sources of emission growth for different pollutants in ASEAN (Source: EC-JRC/PBL, 2019). Notes: PGH- Power generation and heating, RT- Road transportation, MIC- Manufacturing industries and construction, BB- Biomass burning, SF- Solid fuels, FE- Fugitive emissions, RC- Rice cultivation, SWD- Solid waste disposal, WWTD- Wastewater treatment and discharge, MM- Manure management, CP- Cement production, OEI- Other energy industries, IWB- Incineration and open burning of waste, DSE- Direct N2O emissions from managed soils, UA- Urea application.

the highest contribution of NMVOC and CO emissions to Vietnam’s annual RT emissions during 2010–2015. The emission growth in PM, including PM10, PM2.5, BC, and OC, were contributed mainly by biomass burning, ranging from 34–76%. Biomass burning also contributed considerably to CO emission growth between 2000–2015 (Fig. 5). The growth of biomass burning in the region was attributed to large-scale agricultural activities (e.g., open crop residue burning, field burning for agricultural practices) and residential activities (e.g., biofuel burning for cooking and heating) (Lam and Roy, 2021). For CH4 emission growth, the contribution of fugitive emissions from solid fuel, oil, and gas was the largest (52%), followed by rice cultivation, wastewater treatment and discharge, and solid waste discharge. For N2O and NH3, the most substantial portion was from the direct N2O emissions from managed soils (65% and 46%, respectively) (Fig. 5).

4.2 Comparison of Emission Inventories in ASEAN

Table 2 shows the total estimated emissions (SLCP and GHG) from ASEAN for different base years, calculated from various regional EI studies/datasets (Kurokawa et al., 2013; Kurokawa and Ohara, 2020; Ohara et al., 2007; Permadi et al., 2018; Streets et al., 2003) and global EI dataset (EDGAR). The study shows that estimated emissions of pollutants are generally comparable among the same base years, showing an increasing pattern typically for most pollutants throughout the period, with few exceptions. The emissions estimated by Ohara et al. (2007) for the 2000 base year somewhat agree with Streets et al. (2003) for the same base year. However, significant variations in NOx and CO estimation are observed compared with the MICS-Asia II. In 2010, the estimated emissions of most pollutants in MIX-Asian EI were comparable with EDGAR v5.0. However, a significant variation in PM10 and PM2.5 emissions had been observed, which was ~1.8 and ~1.5 times higher than MIX-Asia, while emissions of NH3, CO2, and NMVOC in MIX-Asia were 1.2 to ~1.5 times higher than the EDGAR estimates (Table 2). The estimated total emissions by Permadi et al. (2018) for the 2007 base year were comparatively higher (1.1–1.7 times) than the REAS v2.1 for most of the pollutants except NMVOC and NH3. Like 2010, a similar discrepancy is observed for 2015 EI results between REAS v3.0 and EDGAR v5.0, with higher (1.0–1.7 times) emissions from the EDGAR estimates for most pollutants except CO2 and NH3 (Table 2). These significant variations among the EI results can be due to the uncertainties in local activity data (e.g., fuel consumption in TPP, fuel quality, emission control technology, fuel consumption for
Table 2. Summary of estimated emissions and comparison among the EI works (Gg).

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
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<tr>
<td>SO_2</td>
<td>3649</td>
<td>3319</td>
<td>3150</td>
<td>4560</td>
<td>4212</td>
<td>4596</td>
<td>4449</td>
<td>5149</td>
<td>5396</td>
</tr>
<tr>
<td>NO_x</td>
<td>3771</td>
<td>4122</td>
<td>3058</td>
<td>6703</td>
<td>5549</td>
<td>5320</td>
<td>5120</td>
<td>5806</td>
<td>6240</td>
</tr>
<tr>
<td>CO</td>
<td>54,514</td>
<td>65,675</td>
<td>34,045</td>
<td>55,195</td>
<td>48,324</td>
<td>58,313</td>
<td>50,925</td>
<td>41,053</td>
<td>68,602</td>
</tr>
<tr>
<td>NMVOC</td>
<td>11,090</td>
<td>16,753</td>
<td>–</td>
<td>10,935</td>
<td>14,996</td>
<td>11,553</td>
<td>16,640</td>
<td>12,549</td>
<td>13,284</td>
</tr>
<tr>
<td>PM_{10}</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>4706</td>
<td>3089</td>
<td>5323</td>
<td>3051</td>
<td>3639</td>
<td>5911</td>
</tr>
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<td>–</td>
<td>–</td>
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<td>3300</td>
<td>2278</td>
<td>2511</td>
<td>3663</td>
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<tr>
<td>BC</td>
<td>413</td>
<td>528</td>
<td>321</td>
<td>439</td>
<td>371</td>
<td>430</td>
<td>378</td>
<td>399</td>
<td>477</td>
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<tr>
<td>OC</td>
<td>1833</td>
<td>2918</td>
<td>1370</td>
<td>1558</td>
<td>1421</td>
<td>1474</td>
<td>1452</td>
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<td>28,176</td>
<td>–</td>
<td>–</td>
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<tr>
<td>N_2O</td>
<td>–</td>
<td>–</td>
<td>595</td>
<td>598</td>
<td>522</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>576</td>
</tr>
</tbody>
</table>

Notes: – Not available; * Results of TRACE-P (2001) campaign was used for MICS-Asia II; a,1 Considered as the base year 2000; b CO_2 in Tg; Years in the bracket represents the base year of EI.

heating and cooking, vehicle category, vehicle population, vehicle mileage), data sources (local or international), selection of emission factors (EFs), and methodology chosen for EI development (top-down or bottom-up), also reported in different EI studies (Chen and Meng, 2017; Kurokawa et al., 2013; Pham et al., 2008; Roy et al., 2021a, 2021b; Streets et al., 2003). For instance, in EDGAR, MIX-Asia, or REAS, activity data were obtained from wide-ranging international sources, including IEA, United Nations Energy Statistics Database, International Institute for Applied Systems Analysis (IIASA), Carbon Monitoring and Action (CARMA) database, etc. (Huy et al., 2021; IIASA, 2017; Janssens-Maenhout et al., 2019; Kurokawa et al., 2013; Ohara et al., 2007). Similarly, EFs and emission control efficiency used for EI development, obtained from different international sources, including U.S. EPA AP-42: Compilation of Air Emissions Factors (U.S. EPA, 1995), IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006, 1996), and EMEP/CORINAIR EI Guidebook (EMEP/CORINAIR, 2006). Roy et al. (2021a) reported a significant variation in the newly developed emission inventory for Vietnam thermal power sector compared to other global and regional inventories (e.g., EDGAR, MIX-Asia), mainly due to applying the bottom-up EI approach and considering the plant-specific emission control system for SO_2, NO_x, and particulate matter. While developing EI for thermal power plants and industrial sector in Thailand, Pham et al. (2008) reported discrepancies for SO_2, NO_x, CO, BC, and OC emissions compared to other inventories. The discrepancies are attributed to the selection of EI approach (i.e., top-down vs. bottom-up), variation in emission factors, and consideration of emission control efficiencies (assumed no reduction for the selected emission species, except SO_2). For instance, the estimated BC and OC were two or three times higher than Streets et al. (2003), attributed to the variations in different activity data.

5 SECTORAL EMISSION STATUS IN ASEAN

Sector-specific emissions of pollutants in ASEAN considering four significant emission sectors (i.e., PG, industry, transportation, and residential) were analyzed using the regional (REAS and MIX-Asia) and global (EDGAR v5.0) EI datasets. Results show a considerable variation in emissions in different base years and among the EI datasets of the same base years (Figs. 6(a–f)). Among the four sectors, emission contribution from the residential sector was the largest for most pollutants (CO: 65%, NMVOC: 45%, PM_{10}: 48%, PM_{2.5}: 61%, BC: 81%, OC: 79%, CO_2: 34%) except SO_2 and NO_x in 2000. The emission of SO_2 was much higher from the power (41%) and industrial sector (40%) than other sectors. NO_x emission contribution was the highest from RT (48%), followed by the PG sector (24%). CO_2 emissions were contributed mainly by the residential sector (34%), with a considerable proportion from other sectors (ranged from 17–28%) (Fig. 6(b)). A similar proportion in 2000 is observed from EDGAR v5.0, with the highest contribution from the
residential sector (i.e., 22–82%) for most pollutants (Fig. 6(a)). Huy et al. (2021) reported that the emission contribution of different pollutants, including PM, toxic gases (e.g., CO, VOCs), and GHG from the residential sector, is highly significant in the South Asian region, primarily because of the intensive burning of solid biomass for heating or cooking by a large number of people. According to the Southeast Asia Energy Outlook report, out of ~640 million population, an estimated 250 million are solely dependent on solid biomass for their cooking and other domestic activities, resulting in substantial emissions of PM and gaseous pollutants (IEA, 2017). The study also shows that the emission contributions of SO₂ (51%) and CO₂ (35%) were the highest from the PG sector, while CO and NOₓ were from the transportation sector (49% and 43%, respectively). However, CO emission contribution was also significant from the residential sector (34%) (Fig. 6(a)).

In 2010, sectoral emission contributions (based on the global EI dataset) were like the contribution in 2000, with the most substantial contributions of PM, NMVOC, and NH₃ from the residential sector (ranged from 45–81%), CO, CH₄, and NOₓ from the transportation sector (34–56%), and SO₂ (51%) and CO₂ (42%) from the PG sector. The contribution of NMVOC from the transportation sector was also considerable (44%) (Fig. 6(c)). The MIX-Asian estimate shows a similar emission contribution in 2010 like EDGAR with few exceptions. For instance, unlike the EDGAR, CO, SO₂, and NMVOC were the highest from the residential, industrial, and transportation sector, respectively (Fig. 6(d)). Besides, the proportion of contribution varied significantly for some pollutants. For instance, based on the EDGAR estimate, it is apparent that the power sector contributed the highest SO₂ emission (51%) in 2010, followed by the industrial sector (34%). This contribution varied significantly compared to MIX-Asia (i.e., 36% and 47%, respectively). One possible hypothesis in these discrepancies could be the variation in activity data and emission factors (discussed in Section 4.2) used in EI development. Moreover, the inclusion of different small-scale heating sources along with fossil fuel-based TPPs in EDGAR EI results in significant discrepancies (e.g., variation in SO₂ emissions) between the global and regional EI estimates (EC-JRC/PBL, 2019; Roy et al., 2021a). Li et al. (2017) reported discrepancies among the available emission inventories. For instance, their study showed a significant variation in SO₂ emissions (based on the EDGAR dataset) with other inventories due to lack of information regarding the development activities taken in controlling SO₂ emissions in thermal power plants in China. For CO emissions, discrepancies were also reported, resulting from the underestimation in fuel consumption in residential sector.

In 2015 (EDGAR v5.0), sectoral emission contribution to the total emissions in ASEAN was like the 2010 case (Fig. 6(e)). Regarding the regional EI dataset (REAS), a similar sectoral contribution
pattern was observed, although the proportion of contribution varied compared to EDGAR v5.0 (Figs. 6(e–f)). The results also show a significant emission growth in each sector for the SLCP and GHG between 2000 and 2015. For instance, based on the EDGAR v5.0 dataset, sectoral emission growth ranged from 52.5–837% (PG), 8.2–140.6% (industrial), 10.3–667.5% (transportation), and 8.7–74.3% (residential).

The study also finds that the overall emission contribution of ASEAN to the total emissions in Asia was increased dramatically, which is believed to be because of rapid urbanization and industrial development driven by rapid economic growth. For instance, in 2010, emission contributions from different sectors in ASEAN to the total Asian anthropogenic emissions of pollutants were notable (Fig. 52 in SM). Among the various sectors, the average contribution was the highest from the transportation sector (34%), followed by residential (29%), PG (24%), and industrial sector (14%), respectively, analyzed from the MIX-Asian dataset. However, the ASEAN transportation sector contributes a significant proportion (45%) of total gaseous emissions in Asia. In contrast, the residential and PG sector contributes considerably to the PM emissions (33% and 32%, respectively) (Fig. 52 in SM).

6 COUNTRY-SPECIFIC ANTHROPOGENIC EMISSION TREND

Anthropogenic emission of pollutants in ASEAN countries during 2000–2015 is analyzed using the EDGAR v5.0 EI datasets to show the emission trend and identify the key contributing countries (Fig. 7). In general, an increasing emission trend is observed during this period. For instance, an increasing trend in NOx emission is observed in most ASEAN countries except Singapore. Although Indonesia was the highest NOx emitting country during that period (i.e., ~6 times higher than the average NOx emissions of other ASEAN countries), a significant increase is observed in Vietnam. Emission of NOx has increased by 145% between 2000 and 2015 (i.e., 410.5 vs. 1006.5 Gg), while in Indonesia, it increased by 57% (1531.4 vs. ~2399 Gg) (Fig. 7). We believe that unprecedented growth in vehicle population in major cities in Vietnam (e.g., Hanoi and Ho Chi Minh (HCM)) results in increased NOx emissions. A similar finding has been reported by Roy et al. (2021b), with substantial growth in the on-road vehicle population in Hanoi and HCM, contributing significantly to Vietnam's total RT emissions. IIASA (2017) reported a significant growth rate in the total vehicle (RT) population in Hanoi and HCM between 2005 and 2010 (i.e., 84%), resulting in increased annual RT emissions in Vietnam. The increasing trends for Cambodia, Lao PDR, Myanmar, and Thailand were also notable, with the growth rate of 105%, 85%, 50%, and 47%, respectively. A similar increasing trend in NMVOC emission is observed for most ASEAN countries (except Brunei Darussalam), with the most substantial annual emission from Indonesia. However, NMVOC emission was almost double (~215 vs. ~415 Gg) in Cambodia. Compared to Indonesia, the growth rate was much higher (i.e., 90% vs. 50%) (Fig. 7). The emission trend for Vietnam, Myanmar, and Thailand were also significant, with a 39–48% growth rate between 2000–2015. A rapid increase in vehicle population in the large urban areas of ASEAN (e.g., Jakarta, Bangkok, Manila, Hanoi, HCM) was the possible reason behind the emission growth rate. Studies (Kurokawa et al., 2013; Kurokawa and Ohara, 2020) reported that in Asian regions (including ASEAN), the RT sector is the largest source of NOx and NMVOC, increasing rapidly over time, leading to substantial NOx and NMVOC emissions.

For SO2, an increasing emission trend is observed, with rapid emission growth in Vietnam, Brunei Darussalam, Cambodia, Lao PDR, Malaysia, and Indonesia. Like NOx, the largest growth rate (232%) is found in Vietnam between 2000–2015 (i.e., 313 Gg vs. ~1039 Gg), although the total annual emission was the highest in Indonesia (Fig. 7). The key reason behind the sharp increase in SO2 emission in Vietnam was the uncontrolled emissions from large growing coal-fired TPPs, also reported by Huy and Kim Oanh (2017) and Roy et al. (2021a). A slightly downward emission trend is observed in Thailand after 2013, possibly due to retrofitting emission control systems, including electrostatic precipitators (ESP) or flue gas desulfurization (FGD) to the existing coal-fired TPPs. Emission trends of CO were similar to NMVOC, with the highest growth rate (72%) in Cambodia between 2000–2015 (i.e., ~1345 Gg vs. 2315.5 Gg), followed by Myanmar (53%), Indonesia (34%), and Vietnam (33%) (Fig. 7). Increasing emission trends for BC and OC are observed, with the most substantial emission growth in Cambodia (72–75%), followed by Lao PDR, Singapore,
Fig. 7. Emission trend of different pollutants in ASEAN countries during 2000–2015.
and Vietnam. Kurokawa and Ohara (2020) asserted that increasing diesel and gasoline vehicles in the Asian region leads to an increased emission trend of BC and CO, respectively, while residential combustion leads to increased OC (Zheng et al., 2012). The study also shows that PM$_{10}$ and PM$_{2.5}$ emission trends in ASEAN countries were similar to emission trends of BC and OC, with the highest growth rate in Cambodia (73–79%). Although the total annual emission was more in Indonesia. The emission growth rates in Singapore (51–54%), Vietnam (49–56%), Lao PDR (38–48%), and Thailand (31–32%) were also considerable during that period. Among the GHG, a sharp increasing trend in CO$_2$ emission is observed in all ASEAN countries (Fig. 7), mainly because of a substantial increase in fossil fuel consumption in TPPs, industries, and road vehicles, also reported by Kurokawa and Ohara (2020) for the Asian regions.

The study has identified considerable changes in annual emissions per capita and emissions per sq. km. of land area in the ASEAN countries, analyzed from the World Bank datasets (World Bank, 2021) (Table 3). For instance, in 2000, the high per capita PM$_{2.5}$ emission group (by rank) consisted of Lao PDR, Cambodia, Thailand, Indonesia, and Vietnam (ranked from 5.3–7.1 kg PM$_{2.5}$ per person), while a comparatively lower per capita emission was observed for other ASEAN countries (ranked from 2.3–4.9 kg PM$_{2.5}$ per person). However, a considerable change is observed in 2015 with the per capita emission ranking changes. By rank, the highest per capita emission was in Cambodia (i.e., 9.3 kg per person based on the population of 15,521,435), followed by Lao PDR, Thailand, Vietnam, and Indonesia, respectively. Among the high emission per sq. km of land area per capita group, per capita emission growth in Vietnam was substantial (second largest after Cambodia) between 2000 and 2015 (i.e., ~36%). For Cambodia, the growth rate was 41% (Table 3). Regarding the annual emission per sq. km of the land area during the period, the high emission group (by rank) consists of Singapore, Vietnam, Philippines, Thailand, and Indonesia (ranged from ~676–14,234.3 kg PM$_{2.5}$ per sq. km). Between 2000 and 2015, the emission growth rate per sq. km of land area for all ASEAN countries ranged from 4.6–78.9%. It should be noted that despite the highest emission per sq. km of land area, the total annual PM$_{2.5}$ emissions were much lower in Singapore compared to average emissions of the rest of the ASEAN countries (i.e., 14.42 Gg vs. 405.41 Gg) in 2015. Parker and Bhatti (2020) reported a similar finding for per capita CO$_2$ emissions for the Asian countries. It is also apparent that emission per sq. km of the urban land area was much higher (by rank) for Cambodia, Vietnam, Lao PDR, Myanmar, and Indonesia (ranged from 32,491.7–108,355.5 kg per sq. km). In contrast, the high emission group (by rank) per sq. km of the rural land area consists of Singapore, Vietnam, Thailand, Philippines, and Indonesia (ranged from 743.5–128,435.2 kg per sq. km), with the highest from Singapore (Table 3). It should be mentioned that in 2010, the total rural land area in Singapore was 103.6 sq. km., which was more than 5 times

### Table 3. Annual emission per capita and land area in ASEAN countries.

<table>
<thead>
<tr>
<th>Country</th>
<th>PM$_{2.5}$ Emission in 2000 (kg per capita)</th>
<th>Emission in 2015 (kg per capita)</th>
<th>Emission in 2000 (kg per sq. km land area)*</th>
<th>Emission in 2015 (kg per sq. km land area)*</th>
<th>Emission in 2010 (kg per sq. km urban vs. rural land area)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lao PDR</td>
<td>7.1</td>
<td>Cambodia</td>
<td>9.3</td>
<td>Singapore</td>
<td>14,234.3</td>
</tr>
<tr>
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<td>Lao PDR</td>
<td>8.3</td>
<td>Vietnam</td>
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<tr>
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<td>785.0</td>
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<td>Singapore</td>
<td>2.6</td>
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<td>Brunei</td>
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<tr>
<td>Darussalam</td>
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<td>Darussalam</td>
<td>2.5</td>
<td>Darussalam</td>
<td>196.9</td>
</tr>
</tbody>
</table>

Notes: * Considering country’s total land area (sq. km), excluding area under inland water bodies, national claims to continental shelf, and exclusive economic zones; # Emission per sq. km of urban land area; Values in the brackets represents emission per sq. km of rural land area in 2010.
lower than the total urban land area (i.e., 103.6 vs. 565.6 sq. km). Hence, much higher PM$_{2.5}$ emission per sq. km. of rural area in Singapore was reasonable compared to the emission per sq. km. of urban area (Table 3).

7 SPATIAL DISTRIBUTION OF EMISSIONS

The changes in the spatial distribution of annual emissions of different pollutants between 2000 and 2015 are presented in Fig. 8 and Fig. S3 using the EDGAR annual emission grid maps at 0.1$^\circ$ × 0.1$^\circ$ resolution. Result reveals that the emissions increased significantly between 2000 and 2015 in ASEAN countries. The emission intensity of most pollutants except CH$_4$, N$_2$O, and NH$_3$ was higher in large-growing cities in Thailand (Bangkok, Nonthaburi), Vietnam (Hanoi, HCM, Hai Phong, Can Tho), Malaysia (Kuala Lumpur, Penang, Malacca city), Philippines (Manila, Quezon City), and Indonesia (Jakarta, Surabaya, Bandung, Semarang, and Medan) compared to other areas (Fig. 8 and Fig. S3). Urban areas in ASEAN comprise large populations, on-road (2–4 strokes motorcycles, light-duty vehicles, heavy-duty vehicles, etc.) and off-road (aviation, navigation, and pier) transportation, large-scale and small-scale PG and heating activities, and industrial activities. Thus, high emission intensity in most urban areas in ASEAN is reasonable. In addition, the high emission intensity of CH$_4$, N$_2$O, and NH$_3$ is observed over the rural areas due to the large-scale agricultural practices (e.g., emission from cultivated soil, open crop residues burning, fertilizers application) in Vietnam, Myanmar, Philippines, Indonesia, Thailand, and Cambodia.

In Indonesia, emissions of all pollutants were intense in four major urban areas (Jakarta, Surabaya, Bandung, and Semarang). A significant change in emission distribution is observed in Vietnam compared to the distribution in 2000 from 2015 (Fig. 8 and Fig. S3). Emissions of all pollutants increased significantly in the northern and southern regions of Vietnam due to the increased number of TPPs, vehicle populations (mainly in Hanoi, HCM, and Can Tho city), and industrial development. A similar finding was also reported by Huy and Kim Oanh (2017) and Roy et al. (2021a, 2021b), with much higher emissions from these sectors. For Thailand, high emission
intensity is observed in the central part of the country (Fig. 8 and Fig. S3) due to the most substantial contribution from electricity generation and industrial activities. Pham et al. (2008) asserted that about > 70% of industrial facilities and substantial PG sector in the central region of Thailand have contributed to high SO2, CO, NMVOC, and NH3 emissions.

8 CONCLUSIONS

A rising economy, industrial development, rapid urbanization, and population growth are the main driving forces behind the accelerated anthropogenic emissions of SLCP and GHG in ASEAN countries. The study revealed that the emissions of SLCP and GHG from the selected anthropogenic emission sectors (i.e., PG, RT, industrial, and residential) have increased substantially during 2000–2015 in ASEAN, and the sectoral emission growth ranged from 52.5-837% (PG), 10.3-667.5% (RT), 8.2–140.6% (industrial), and 8.7–74.3% (residential). Among the ASEAN countries, a notable increase in emissions has been observed in Cambodia, Lao PDR, Myanmar, and Thailand for most of the pollutants, although the annual emissions were more in Indonesia. The key reasons behind the large growth in annual emissions during the period include large-scale PG activities (e.g., coal-fired TPPs) to satisfy the increased electricity demand in multiple sectors, unprecedented growth in vehicle population, industrial combustion, and fuel-burning for residential cooking or heating. In terms of spatial distribution, the emission intensity of most pollutants was higher in the major urban areas of Vietnam, Thailand, Malaysia, Philippines, and Indonesia except CH4, N2O, and NH3, which were more in the rural areas. This crucial information of ASEAN emission trends, sectoral and country-specific emission status, and spatial changes in emissions will help promulgate regulatory measures and policies concerning local and regional emission mitigation and air quality management within ASEAN. Evaluation and advancement in the existing study should be conducted based on the updated emission data on ASEAN in the regional and global datasets (usually update 3–5 years interval). As most ASEAN countries have already approved/implemented regulatory measures to reduce anthropogenic emissions in different sectors (e.g., TP, RT) to comply with the international agreement (e.g., COP21 or COP26), advancement in the current study would be vital to evaluate the effects of policy intervention on ASEAN emission trends, sectoral and country-specific emission contribution, and spatial changes in emission.

SUPPLEMENTARY MATERIAL

Supplementary material for this article can be found in the online version at https://doi.org/10.4209/aaqr.220103

REFERENCES


Chen, L., Gao, Y., Zhang, M., Fu, J.S., Zhu, J., Liao, H., Li, J., Huang, K., Ge, B., Wang, X., Lam, Y.F., Lin,


Roy, S., Lam, Y.F., Hung, N.T., Chan, J.C.L., Fu, J.S. (2021b). Development of 2015 Vietnam...


