

QUANTIFICATION AND ANALYSIS OF PM_{2.5} AND ITS PRECURSORS USING GAIN MODEL IN PUNJAB, PAKISTAN

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ABSTRACT: The study for Punjab, Pakistan, used the GAINS South Asia model 2 to analyze emissions data and control measures. It relied on the "Final Report: Baseline08" scenario, which integrated legislative actions up to 2008. The GAIN Model's Scenario: PAKI_BAU_CPS_2021 was employed for emissions calculations, focusing on PM_{2.5} and its precursors. In 2020, major sources of PM_{2.5} emissions included residential combustion (42.4%), industrial processes (20.8%), and industrial combustion (14.6%). However, the modeled contribution of vehicles to PM_{2.5} was surprisingly low indicating that model has used low emission factors for vehicles in Punjab. Heavy-duty diesel vehicles (34.9%) were the primary sources of NO_x emissions, with agriculture, light-duty vehicles, and power and heating plants also contributing 16% each to NO_x emissions. SO₂ emissions predominantly came from local coal, furnace oil, and diesel, primarily from power and heating plants (46.4%) and industrial combustion (30.7%). Agriculture was the dominant source of NH₃ (91.7%) emissions. VOCs primarily originated from residential combustion (54.6%), light-duty vehicles (19.1%), and solvents. Black Carbon (BC) emissions had their major sources in residential combustion (58%). Actual data from Lahore also emphasized the significant vehicular contribution to PM_{2.5} emissions. The data suggests that OC and EC together form 39% of PM_{2.5} in busy areas of Lahore, highlighting vehicles as a major pollutant source. NH₄NO₃ and (NH₄)₂SO₄ collectively contribute 37% to PM_{2.5}, with NO₃ at 13% surpassing SO₄'s 11%. Model data indicates SO₂ at 482.8 Kt/yr and NO_x at 661.5 Kt/yr. Despite NH₃'s significant 994 Kt/yr contribution, mainly from agriculture, NH₄ levels are modest due to non-agricultural data sources. Notably, the GAIN model may have underestimated vehicle emission factors, with actual data indicating a potentially higher contribution from vehicles to various pollutants.

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INTRODUCTION

Air pollution in Punjab, Pakistan, is a pressing issue influenced by various factors, such as rapid urbanization, increased vehicular traffic, and industrialization. Over recent years, especially in Lahore, the province's capital, there have been severe episodes of smog, particularly during the winter months, which not only hamper visibility but also pose substantial health risks to the population (World Bank, 2018). One of the significant contributors to this pollution, especially during post-harvest seasons, is the burning of rice stubble by farmers. This act introduces a significant amount of particulate matter, carbon monoxide, and volatile organic compounds into the atmosphere. Moreover, with Lahore and other major cities in Punjab witnessing an exponential increase in vehicles, many of which are old and poorly maintained, the emissions of pollutants such

as NO_x, CO, and particulate matter have surged (Colbeck *et al.*, 2010). Furthermore, Punjab's status as an industrial hub means that factories, including brick kilns, cement plants, and power generation units, are significant contributors to the region's air pollution. Dust from construction activities, vehicular movements on unpaved roads, and a lack of greenery in certain urban zones further add to PM_{2.5} and PM₁₀ levels. In rural areas and some urban pockets, the utilization of substandard fuels like wood, coal, and animal dung for cooking and heating produces indoor pollutants, which also add to outdoor pollution levels. Cross-border pollution from neighboring regions has occasionally been identified as a factor influencing Punjab's air quality, although the precise contribution of such sources often becomes a matter of debate. To combat the escalating air pollution levels, the Punjab government has launched several initiatives. These comprise the formulation of a smog policy and associated action plan, introducing regulations for

industries like brick kilns, imposing bans on crop residue burning during specific intervals, and inaugurating air quality monitoring stations in various parts of the province (World Bank, 2018). However, challenges like effective regulation enforcement, raising public awareness about pollution's health impacts, and the scarcity of comprehensive pollution source data continue to persist.

PM_{2.5}, or particulate matter with a diameter less than 2.5 micrometers, is a major air pollutant of concern due to its potential adverse effects on human health. PM_{2.5} particles are small enough to penetrate deep into the lungs and can even enter the bloodstream. These particles are a complex mixture of solid and liquid droplets arising from various sources and atmospheric processes. This is primarily emitted from the burning of fossil fuels by power plants and other industrial facilities. In the atmosphere, SO₂ can be oxidized to form sulfate particles, which contribute to PM_{2.5} (Fenger, 2009). Nitrogen Oxides (NO_x), emitted from transportation sources, power plants, and other combustion processes, NO_x can be transformed in the atmosphere into nitrate particles, another component of PM_{2.5} (Seinfeld and Pandis, 2016). Ammonia (NH₃), mainly originating from agricultural activities, especially livestock waste and fertilization, ammonia can react with acidic pollutants like SO₂ and NO_x to form ammonium sulfate and ammonium nitrate particles respectively, both of which are components of PM_{2.5} (Pinder *et al.*, 2007). Volatile Organic Compounds (VOCs), emitted from a variety of sources including vehicles, industrial processes, and vegetation. Some VOCs can undergo reactions in the atmosphere to produce secondary organic aerosols, which contribute to PM_{2.5} (Hallquist *et al.*, 2009). Carbonaceous Materials, this includes organic carbon and elemental carbon. Organic carbon can come from direct emissions (like vehicle exhaust) or can be formed in the atmosphere from VOCs. Elemental carbon, often referred to as soot, is emitted from combustion processes, particularly diesel combustion (Bond *et al.*, 2013). The aforementioned precursors undergo complex atmospheric reactions influenced by various factors, such as sunlight, temperature, and humidity, leading to the formation and growth of PM_{2.5} particles.

Energy production and consumption are among the primary contributors to air pollution globally. Different energy sectors release various pollutants, depending on the energy source, technology, and pollution control measures in place. Here's a breakdown of the contribution to air pollution by different energy sectors with in-text reference. Among the most polluting energy sectors, coal combustion releases a significant amount of sulfur dioxide (SO₂), nitrogen oxides (NO_x), particulate matter (PM), and mercury (Hg) (Pope III *et al.*, 2011). Coal burning also emits carbon dioxide (CO₂), a significant greenhouse gas. Oil refineries emit various

pollutants, including SO₂, NO_x, VOCs, and PM. Combustion of gasoline in vehicles releases NO_x, VOCs, CO, and PM. Natural gas, though cleaner than coal or oil, still emits NO_x and CO₂ when burned (McCarthy *et al.*, 2015). Burning biomass (like wood, crop residues, and dung) in inefficient stoves or open fires for cooking and heating is a major source of indoor and outdoor air pollution. It primarily emits PM, CO, and various VOCs (Smith *et al.*, 2014). Industries, especially cement production, steel manufacturing, and chemical industries, release pollutants including SO₂, NO_x, CO, PM, VOCs, and various toxic compounds (Chen *et al.*, 2018). While significantly cleaner in terms of air pollutant emissions, the manufacturing, installation, and maintenance of renewable energy technologies (like solar panels and wind turbines) have some environmental impact, albeit much less in comparison to fossil fuel-based sectors (Hertwich *et al.*, 2015). Road, marine, and air transport contribute significantly to NO_x, CO, VOCs, and PM emissions. Vehicles, especially diesel ones, can be a significant source of PM_{2.5} and NO_x in urban areas (Bishop *et al.*, 2010). While waste-to-energy plants can help reduce landfill waste, they can emit dioxins, furans, mercury, and PM if not adequately managed and equipped with pollution control technologies (Themelis and Ulloa, 2007).

The Greenhouse Gas - Air Pollution Interactions and Synergies (GAINS) model, developed by the International Institute for Applied Systems Analysis (IIASA), serves as an integrated assessment model aimed at offering a comprehensive perspective on air pollution and greenhouse gas emissions (Amann *et al.*, 2011). By considering multiple pollutants and the intricate ways in which they interact, the GAINS model provides insights into the environmental, health, and economic consequences of various policy options, thereby equipping policymakers with the knowledge needed to devise effective strategies.

Within its framework, GAINS quantifies the emissions of major air pollutants and greenhouse gases, tracing their transport and transformation within the atmosphere. It then assesses the subsequent environmental impacts, which include, among others, the effects on human health due to fine particulate matter and ground-level ozone, as well as ecosystem disturbances such as eutrophication and acidification (Klimont *et al.*, 2001). A notable feature of the GAINS model is its capability to pinpoint cost-effective emission reduction strategies that cater to both immediate air quality objectives and long-term climate goals. By adopting an integrated approach, the model ensures a comprehensive understanding of the potential co-benefits and trade-offs that arise between air pollution control measures and climate mitigation strategies.

Through its evaluation of a wide range of technological solutions and policy measures, GAINS

provides an overview of the potential, costs, and benefits of reducing emissions, and the ensuing environmental impacts (Amann *et al.*, 2011). As such, the GAINS model has emerged as a critical instrument for both researchers and policymakers, particularly in discussions surrounding international policy negotiations and the broader realm of air quality management.

MATERIALS AND METHODS

The GAINS model estimates emissions bottom-up, i.e., quantifications of human activities contributing to emissions are multiplied by an emission factor representing the average emissions per unit of activity. Such estimates rely on a wealth of publicly available information to develop internally consistent emission factors across countries, sectors and technologies (Höglund-Isaksson L., *et al.*, 2020). Emissions are calculated using Scenario: PAKI_BAU_CPS_2021 of the Gain Model. Contribution of different sectors towards air pollution in Punjab is given in Table 1.

The GAINS South Asia model 2 was employed to gather emissions statistics and pertinent control details for Punjab Pkaistan. The analysis utilized the default scenario titled "Final Report: Baseline08" (updated last in September 2008). This scenario was crafted based on findings from the GAINS-Asia project funded by the EU (IIASA, 2008), incorporating the execution of all legislations up to the year 2008.

For a comprehensive analysis, the data extracted from GAINS was transferred to an offline Excel database. Information from GAINS outputs was directly copied into Excel, forming the platform where the analysis took place. It's crucial to highlight that the sole source of primary data for this report was the GAINS South Asia model, with no other resources being utilized for raw data acquisition.

Gain model is used to calculate annual emission production of PM2.5 and its precursors other than natural dust like NO_x, SO₂, NH₃, VOCs and BC. Model is also used to findout energy used by different sectors like Power and heating plants, Fuel conversion, Residential combustion, Industrial combustion, Industrial processes, Solvents, Fuel production and distribution, Light duty vehicles, Heavy duty vehicles-diesel, Non-road machinery, Agriculture, Waste, Nonenergy use of fuels.

RESULTS AND DISCUSSION

Contribution of different Sectors to PM2.5 and its precursors: Table 1 highlights the contribution by different sectors to PM2.5 and its precursors. The major source of NO_x emissions is heavy-duty diesel vehicles (34.9%). High temperature of diesel engines contributes towards production of NO_x emissions. Contribution from

Agriculture, light duty vehicles and Power and Heating Plants is almost 16% from each sector. The production of NO_x from agriculture is due to natural factors.

Power and heating plants and Industrial Combustion using furnace oil or coal rich in sulfur are major contributor for SO_x emissions with 46.4% and 30.7% contribution respectively.

The major source of NH₃ is simply agriculture (synthetic fertilizer) with 91.7% contribution.

Major source of VOCs are residential combustion, light duty vehicles and solvents with 54.6%, 19.1% and 11.9% respectively.

Major source of PM2.5 are residential combustion, industrial processes and industrial combustion with 42.4%, 20.8% and 14.6% contribution. Power plants contribute 9.1%. The contribution of vehicles is almost negligible which looks questionable.

Major contributors towards Black Carbon (BC) are residential combustion, industrial combustion and light duty vehicles with 58, 16.6 and 9.1% contribution respectively. Contribution of different sectors towards air pollution is given in Table 1.

Figure 1 shows percentage contribution by different sectors to PM2.5 and its main precursors (NO_x, SO₂, NH₃, VOCs, BC) other than natural dust (2020) obtained through GAIN Model. The highest contribution is of residential combustions (26%), while residential combustion uses 49% of overall energy. Agriculture is the only major contributor to NH₃, but overall contributes to 28%. Light and heavy duty vehicles as a whole contributes to 16% of PM2.5 and its precursors air pollution. Power plants, industrial combustion and industrial processes account for 10%, 8%, and 6% of PM2.5 and its precursor's air pollution respectively.

Energy usage by different Sectors in Punjab: Punjab, Pakistan, demonstrates varied energy consumption patterns across its many sectors. Households predominantly rely on electricity and natural gas for lighting, appliance use, and heating needs. The industrial sector, with a strong focus on textiles and manufacturing, utilizes a considerable volume of electricity and gas, with textiles being a standout consumer. The transportation arena in Punjab is majorly fueled by petroleum derivatives, notably gasoline and diesel, reflecting the province's urban growth and increasing vehicular count. Being Pakistan's agricultural centerpiece, Punjab's farming sector consumes significant energy. Electricity is chiefly harnessed for irrigation, while diesel propels machinery such as tractors and tube wells. Commercial spaces in Punjab, spanning from shops and offices to markets, largely utilize electricity for lighting and other operational needs. In contrast, natural gas finds extensive use in heating and culinary processes, especially within dining establishments. Moreover, public entities like government facilities, educational establishments, and

hospitals contribute to the overall energy footprint of Punjab.

Figure 2 shows energy usage by different sectors in Punjab. Total energy usage is 2113 PJ/Yr in 2020. Punjab is the most populous province in Pakistan. As per the 2017 census data, the population of Punjab was estimated to be around 110 million (Pakistan Bureau of

Statistics, 2017). Due to such high population of Punjab, the model shows 49% energy usage by households. Industrial combustions is the second highest energy usage sector with 19% energy usage. Light duty vehicles, heavy duty vehicles and power plants uses 11%, 9% and 7% energy respectively. Vehicles as a whole use 20% energy (422 PJ/Yr).

Table 1: Percentage Contribution of different sectors to PM2.5 and its main precursors other than natural dust in Punjab during 2020, obtained through GAIN Model.

	NO _x	SO ₂	NH ₃	VOCs	PM _{2.5}	BC
Power and heating plants	15.9%	46.4%	0.0%	1.5%	9.1%	2.4%
Fuel conversion	0.3%	2.4%	0.0%	0.1%	0.2%	0.1%
Residential combustion	7.0%	5.8%	0.6%	54.6%	42.4%	58.0%
Industrial combustion	4.7%	30.7%	0.0%	0.9%	14.6%	16.6%
Industrial processes	3.9%	2.9%	1.1%	0.0%	20.8%	0.2%
Solvents	0.0%	0.0%	0.0%	11.9%	0.1%	0.4%
Fuel production and distribution	0.0%	0.0%	0.0%	1.6%	1.6%	5.0%
Light duty vehicles	16.3%	7.7%	0.2%	19.1%	1.9%	9.1%
Heavy duty vehicles-diesel	34.9%	3.5%	0.0%	2.5%	0.5%	0.8%
Non-road machinery	0.2%	0.1%	0.0%	0.0%	0.0%	0.1%
Agriculture	16.6%	0.5%	91.7%	7.7%	7.3%	6.0%
Waste	0.0%	0.0%	6.4%	0.0%	1.5%	1.1%
Nonenergy use of fuels	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

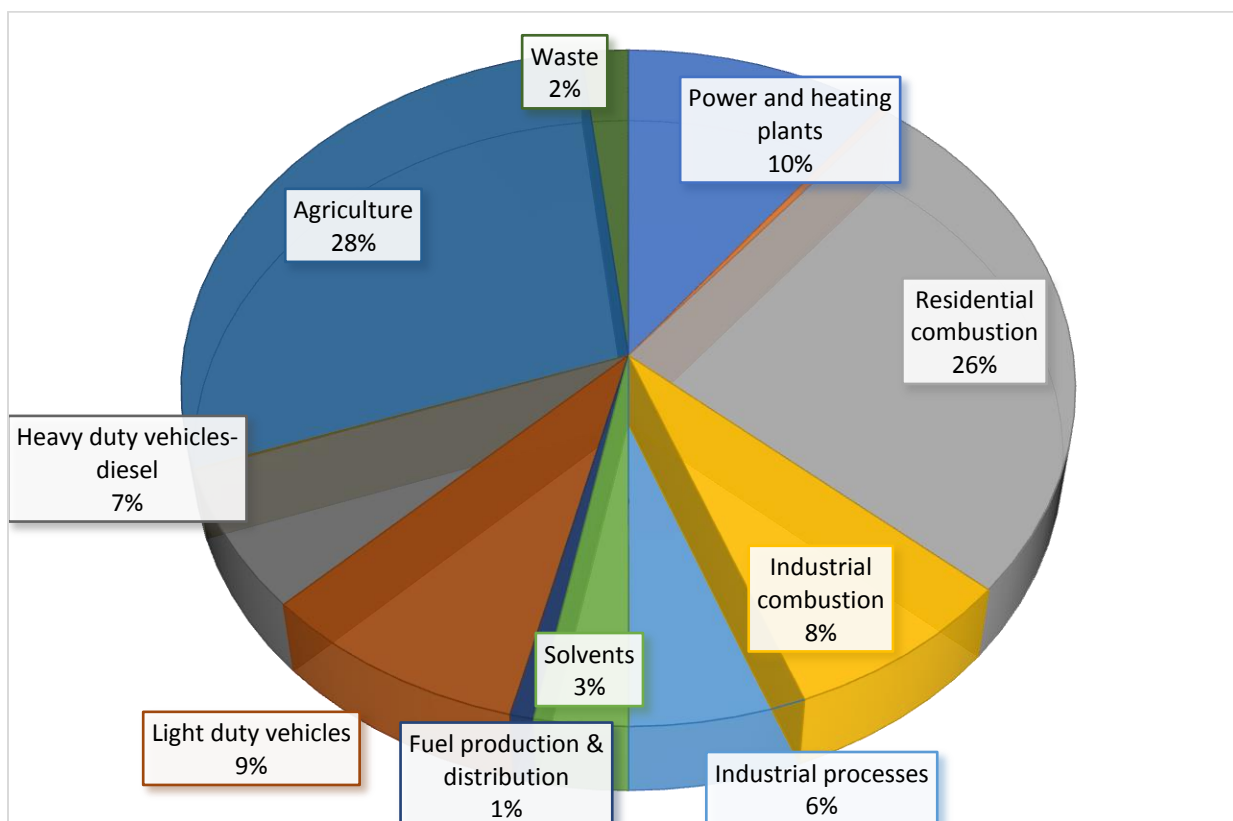


Figure 1: Contribution by different sectors to PM2.5 and its main precursors (NO_x, SO₂, NH₃, VOCs, BC) other than natural dust (2020) obtained through GAIN Model

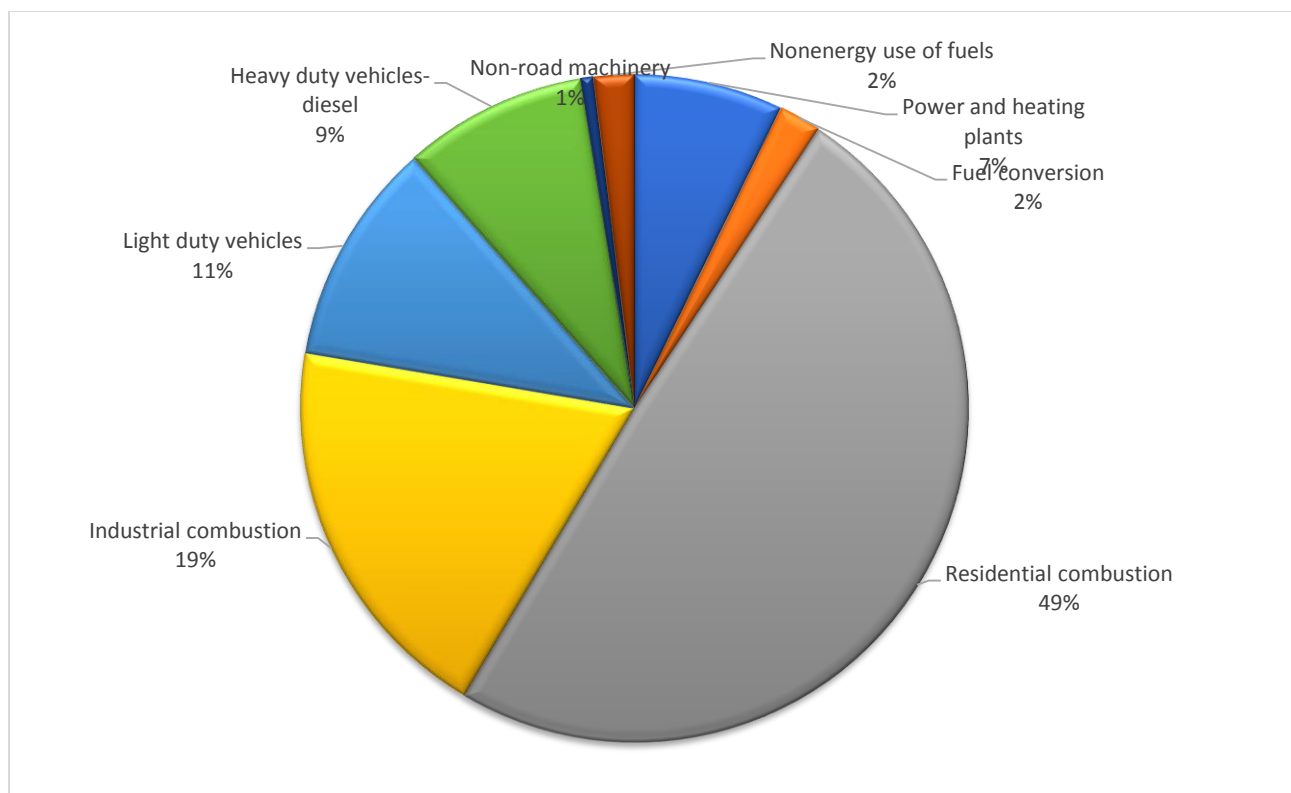


Figure 2: Energy usage [PJ/yr] by different sectors during 2020 in Punjab obtained through GAIN Model

Analysis of the level of PM_{2.5} and its precursors:

Table 2 shows the level of PM_{2.5} and its precursors produced by different energy sectors during 2020. Table 3 shows the level of PM_{2.5} and its components during monthly monitoring in 2022.

Nitrogen and oxygen reacts to form NO_x at high temperature in different engines mostly. The chief source of NO_x is the combustion of fossil fuels in car engines and power plants. When these fuels combust, the generated heat prompts nitrogen in the combustion air to combine with oxygen, yielding NO and NO₂ (Finlayson-Pitts and Pitts, 1999).

Apart from vehicular and power plant emissions, industrial processes, like manufacturing and energy production, are other notable NO_x contributors. In such processes, high-temperature operations induce the nitrogen in the air to oxidize. Natural phenomena, including lightning, result in NO_x emissions too. The energy from lightning causes the atmospheric nitrogen to react with oxygen, generating NO_x. Agricultural and natural soils also release NO_x, primarily as NO, due to microbial processes in the presence of organic nitrogen compounds. (Seinfeld and Pandis, 2016). According to GAIN model main sources of NO_x are heavy duty vehicles, fertilizer based agriculture, light duty vehicles and power and heating plants with 230.8, 110, 108 and 105 Kt/yr total NO_x emissions during 2020 respectively.

Local coal, furnace oil and diesel are main source of SO₂ in Punjab Pakistan. According to Gain Model main sources of SO₂ are power and heating plants, industrial combustion, light duty vehicles and heavy duty vehicles with 224, 148, 37 and 16 Kt/yr total SO₂ emissions during 2020 respectively.

Punjab predominantly uses urea, DAP (Diammonium Phosphate), NP (Nitrophos), and other nitrogenous, phosphatic, and potassic fertilizers. Urea, being a nitrogenous fertilizer, is the most commonly used type. When applied to the soil, a portion of the nitrogen in urea and other nitrogenous fertilizers is converted to ammonia. Fertilizer based agriculture and waste are the main source of NH₃ emissions with 911.7 and 63 Kt/y total NH₃ emissions during 2020 in Punjab as obtained from the GAIN Model.

Main sources of VOCs are residential combustion, light duty vehicles, solvents and agriculture with 585, 205, 127 and 82 Kt/yr respectively. Heavy duty vehicles are also responsible to some extent with 27 Kt/yr VOCs emissions.

Main sources of PM_{2.5} are residential combustion, industrial processes, industrial combustion and power and heating plants with 386.8, 189.9, 133 and 82.9 Kt/yr PM_{2.5} emissions during 2020 respectively.

Main sources of black carbon are residential combustion, industrial combustion and light duty vehicles with 56.4, 16.2 and 8.9 Kt/y respectively. It looks that

Gain model has assumed low emission factor for vehicles, but in case of Punjab Pakistan there could be much high emission factors of vehicles in terms of PM2.5, VOCs, BC, EC and OC. Actual results given in Table 3 depicts that OC and EC as a whole makes 39% of the PM2.5 near busy road of Lahore. Actual results (Table 3) indicates high contribution to PM2.5 from vehicles.

Table 3 shows that NH₄NO₃ and (NH₄)₂SO₄ as a whole makes 37% of PM2.5. The contribution of NO₃

(13%) is greater than SO₄, which resembles the model results with 482.8 Kt/yr contribution for SO₂ and 661.5 Kt/yr for NO_x. The contribution of NH₃ (994Kt/yr) is greater than both NO_x and SO₂, but the production of NH₃ is only from the agriculture sector. Because the actual results (Table 3) have not been taken from agricultural fields thereby NH₄ level is not so high as compared to NO₃ and SO₄.

Table 2: Contribution of different sectors to PM2.5 and its main precursors other than natural dust in Punjab during 2020, obtained through GAIN Model.

	NO _x	SO ₂	NH ₃	VOCs	PM2.5	BC
	[kt/yr]	[kt/yr]	[kt/yr]	[kt/yr]	[kt/yr]	[kt/yr]
Power and heating plants	105.2	224.1	0.1	16.2	82.9	2.3
Fuel conversion	2.2	11.8	0	0.8	1.4	0.1
Residential combustion	46.5	28.2	6.1	585.2	386.8	56.4
Industrial combustion	30.9	148.1	0	9.8	133.1	16.2
Industrial processes	25.8	14	11.1		189.9	0.2
Solvents				127	0.5	0.4
Fuel production and distribution	0.3	0	0	17.5	14.3	4.9
Light duty vehicles	108	37.4	1.7	205	17.7	8.9
Heavy duty vehicles-diesel	230.8	16.8	0.1	27	4.6	0.8
Non-road machinery	1.6	0.3	0	0.4	0.2	0.1
Agriculture	110.1	2.2	911.7	82.2	66.6	5.8
Waste	0	0	63.4	0	13.6	1.1
Nonenergy use of fuels						
Sum	661.5	482.8	994.2	1071.2	911.6	97.3

Table 3: Concentration of PM2.5 (µg/m³) and its precursors other than natural dust during 2022.

	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC	Ave.	%age
PM2.5	177.8 9	111.58	108.29	105.2 7	74.33	74.8	45.05	31.22	82	106.51	222.02	186.16	110.43	
Sulfate	16.31	15.93	15.34	10.37	8.8	9.2	4.75	4.41	11.07	14.85	20.87	15	12.24	11
Nitrate	17.28	16.98	19.05	13.13	8.16	7.94	7.47	7.99	10.91	18.36	29.35	18.4	14.59	13
Ammonium	15.4	16.4	14.2	13.6	12.5	12.2	10.8	11.2	14.8	16.4	18.2	17.6	14.44	13
OC	37.44	27.36	26.4	27.84	24.96	23.04	19.28	12.32	15.28	31.2	65.28	58.56	30.75	28
EC	17.28	13.44	12.24	9.84	10.56	9.12	10.56	8.08	11.52	12.24	19.68	15.36	12.49	11

Conclusion: To understand emissions data and associated control measures for Punjab, Pakistan, the GAINS South Asia model 2 was utilized. The study primarily hinged on the "Final Report: Baseline08" scenario, updated last in September 2008. This foundational scenario drew inspiration from the GAINS-Asia project, funded by the EU, which covered all legislative actions up to 2008 (IIASA, 2008). Furthermore, the GAIN Model's Scenario: PAKI_BAU_CPS_2021 was instrumental in emission calculations.

The extracted GAINS data was methodically transferred to an Excel database for a deeper analysis.

This Excel platform enabled a detailed inspection of the data.

Through the GAIN model, the annual emissions of PM2.5 and its precursors, minus the natural dust components, were detailed. This covered agents like NO_x, SO₂, NH₃, VOCs, and BC. Additionally, the model illuminated energy consumption patterns across sectors including power and heating plants, residential combustion, and industrial activities, to name a few.

In 2020, primary sources of PM2.5 were identified as residential combustion (42.4%), industrial processes (20.8%), and industrial combustion (14.6%). The contributions of power plants were marginally less at

9.1%. A peculiar observation was the limited contribution from vehicles to PM_{2.5} emissions.

NO_x emissions in 2020 were chiefly from heavy-duty vehicles, particularly diesel engines, at 34.9%. High combustion temperatures in these vehicles were largely responsible for the emissions. Other significant contributors were agriculture, light-duty vehicles, and power and heating plants, each at about 16%. Interestingly, the agricultural emissions of NO_x were naturally derived.

Sulfur dioxide (SO₂) emissions predominantly emanated from local coal, furnace oil, and diesel sources. Major contributors, as per the GAIN Model, in 2020 included power and heating plants and industrial combustion units. Those leveraging sulfur-laden furnace oil or coal led the SO_x emissions chart with significant contributions.

Regarding ammonia emissions in 2020, the chief contributor was agriculture, especially due to the use of synthetic fertilizers like urea, with an overwhelming 91.7% contribution. VOCs, in the same year, were traced back mainly to residential combustion (54.6%), light-duty vehicles (19.1%), and solvents (11.9%). Black Carbon (BC) emissions had its major sources in residential combustion at 58%, followed by industrial combustion and light-duty vehicles.

The actual data reveals that the combined contributions of OC and EC account for 39% of the PM_{2.5} levels around Lahore's congested roads, underscoring the substantial impact of vehicular emissions on PM_{2.5} concentrations.

Actual results further indicate that NH₄NO₃ and (NH₄)₂SO₄ together constitute 37% of PM_{2.5}. While NO₃'s contribution (13%) exceeds that of SO₄ (11%), this is in line with the model's outputs showing 482.8 Kt/yr for SO₂ and 661.5 Kt/yr for NO_x. NH₃, contributing 994 Kt/yr, surpasses both NO_x and SO₂, though its primary source is agriculture. Given that the actual weren't sourced from agricultural regions, NH₄ concentrations appear relatively subdued compared to NO₃ and SO₄.

While the GAIN model may have estimated vehicles' emission factor on the lower side, actual data from Lahore suggests vehicles could have a higher emission potential, particularly for PM_{2.5}, VOCs, BC, EC, and OC. Indeed, data from a bustling Lahore street suggests vehicular exhaust was a dominant PM_{2.5} contributor.

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