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Review

Adjustment Criteria for Air Quality Standards by Altitudes: A Scoping Review with Regulatory Overview

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Abstract: Air quality standards (AQS) are key regulatory tools to protect public health by setting pollutant thresholds. However, most are based on sea-level data. High-altitude (HA) environments differ in atmospheric conditions, influencing pollutant behavior and human vulnerability. These differences have prompted proposals for altitude-specific AQS adjustments. This systematic review identifies models and criteria supporting such adaptations and examines regulatory air quality frameworks in countries with substantial populations living in very high-altitude. This review followed PRISMA-P guidelines, focusing on studies examining *AQS* adjustment approaches based on altitude. The Population/Concept/Context (PCC) framework was used to define search terms: Population (AQS), Concept (Air Pollutants), and Context (Altitude), with equivalents. Literature was retrieved from MEDLINE, SCOPUS, Web of Science and Gale OneFile: Environmental Studies and Policy. A total of 2,974 articles were identified, with 2,093 remaining after duplicate removal. Following title and abstract screening, 2,081 papers were excluded, leaving 12 for full-text evaluation. Ultimately, six studies met the eligibility criteria. Three studies focused on adjustment models based on atmospheric conditions, such as temperature and pressure changes, while the other three examined human physiological responses, particularly the increased inhaled air volume. China, Peru, and Bolivia have the largest populations living above 3,500 m a.s.l., yet none of these countries have specific air quality regulations tailored to HA conditions. The review underscores the necessity for tailored AQS in HA environments, highlighting specific criteria related to both atmospheric conditions and human physiological responses.

Keywords: Altitude; Air Quality Standards; pollution; adjustment; scoping review

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1. Introduction

The World Health Organization (WHO) estimates that 99% of the global population breathes air with pollutant levels exceeding recommended limits, making it the primary environmental medium for pollutant exposure and the second leading risk factor for death worldwide (Health Effects Institute, 2024; WHO, 2022). Outdoor air pollution is responsible for nearly 7 million excess deaths annually, with the highest burden observed in low- and middle-income countries. This critical situation underscores the need to strengthen public health policies aimed at reducing pollution levels (Feng et al., 2024; Jonidi Jafari et al., 2021).

Air Quality Standards (AQS) are legally binding instruments and essential components of public health strategies aimed at managing exposure to air pollutants (Kutlar Joss et al., 2017). They establish pollutant concentration thresholds and objectives to minimize the risk of adverse health effects (Fowler et al., 2020; UNEP, 2021). Most countries develop their national (or federal) AQS primarily based on international guidelines provided by organizations such as the World Health Organization

(WHO), the U.S. Environmental Protection Agency (EPA), and the European Environment Agency (EEA), among others (Shairsingh et al., 2023; Wooley et al., 2024).

These guidelines offer evidence-based recommendations derived primarily from a systematic analysis of environmental epidemiology studies conducted predominantly in metropolitan areas with adequate resources and well-established monitoring networks (Ravindra et al., 2024; Shairsingh et al., 2023). However, these conditions may not be replicable in developing countries, which often feature diverse environmental settings and limited air quality management infrastructure (Vahlsing and Smith, 2012). In this context, the guidelines highlight the need to adapt air quality target values to local conditions before implementing international standards (WHO, 2021).

High-altitude (HA) environments can significantly influence pollution levels and impact population exposure (Masiol et al., 2024). A 1978 report by EPA highlighted that HA atmospheric conditions—such as reduced barometric pressure, lower temperatures, increased solar radiation, and other factors—affect pollutant dynamics through various mechanisms (U.S. EPA, 1978). These include intensifying photochemical reactions, increasing the frequency of thermal inversions, promoting aerosol formation, dispersion, deposition, condensation, and altering vehicle emissions, among others (Dordević and Šolević, 2008; Herrmann et al., 2015).

The respiratory physiology of native HA populations is another critical factor to consider in this context (Bigham et al., 2013; Storz, 2021). Over generations, these populations have developed anatomical and physiological adaptations that enhance lung capacity, allowing them to cope with hypoxic conditions at altitudes (Moore, 2001). As a result, they exhibit higher ventilatory rates than sea-level populations, leading to the inhalation of larger air volumes—and consequently, greater exposure to airborne pollutants (Li et al., 2024).

These conditions underscore the numerous variables that pose a complex challenge when considering the need for altitude-specific AQS (Ortiz-Prado et al., 2022). However, previous research in the biological field has demonstrated that adjusting parameters based on biological markers is feasible (Dzhalilova and Makarova, 2020). A notable example is the classification criteria for anemia at high altitudes, where a non-linear increase in blood hemoglobin (Hb) levels has guided the establishment of specialized reference values and clinical decision thresholds for these populations (Sullivan et al., 2008).

Altitude-dependent pollution dynamics are particularly critical for rapidly expanding HA cities, where emissions and meteorological challenges are exacerbated by urbanization and population growth (Ehrlich et al., 2021). Approximately 81 million people live at altitudes above 2,500 meters above sea level (m a.s.l.), with major population centers located in low- and middle-income regions, such as the Tibetan Plateau in China and the Andean countries in South America (Tremblay and Ainslie, 2021).

It is well known that these countries often enforce less stringent regulations, frequently exceeding both AQS and WHO guidelines (Wiedensohler et al., 2018). The combined effect of overexposure and altitude may help explain the higher prevalence of respiratory diseases associated with air pollution—such as asthma—among individuals living at HA compared to those at sea level (Guo et al., 2020; Vargas et al., 2018). Furthermore, this issue remains largely underexplored, exposing a social inequality gap driven by inadequate regulatory frameworks in these regions.

This scoping review aims to identify available literature that address setting AQS adapting to altitude environments and the factors implying it. Additionally, it seeks to summarize existing regulations regarding AQS in major HA countries, discussing the criteria and conditions relevant to protecting the health of populations living at very HA. This review highlights gaps and opportunities for developing effective air quality guidelines tailored to specific contexts and for establishing public policies and regulations that prioritize health protection.

2. Methods

We conducted a scoping review to inform the proposed models and criteria for adjusting air quality standards (AQS) to altitude, complemented by an overview of regulations AQS applied in countries with a higher proportion of the population living in HA cities.

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2.1. Protocol Registration and Search Strategies

This study follows the PRISMA-P (Preferred Reporting Items for Systematic Review and Meta-Analysis Protocols) guidelines to ensure transparency, reproducibility, and quality throughout the review process. We utilized the Population/Concept/Context (PCC) framework to define and organize the search terms. These terms included Population (Air Quality Standards), Concept (Air Pollutants), and Context (Altitude), along with their corresponding equivalents identified through PubMed MeSH and PAHO DeCS web portals. The protocol was designed a priori and registered on the Open Science Framework (OSF) platform, available at https://osf.io/c3fnh/.

This review was conducted using literature from key databases, including MEDLINE, SCOPUS, Web of Science, and Gale OneFile: Environmental Studies and Policy. Detailed search algorithms are provided in Supplementary material 1. The search strategy was designed to avoid duplication of existing systematic reviews, ensuring the novelty and relevance of the present study. For the overview of AQS regulations, we focused on countries with the largest populations living above 3,500 m.a.s.l.: China, Peru, and Bolivia (Tremblay and Ainslie, 2021). Reports on air quality regulations from the environmental agency repositories of these countries were analyzed and summarized alongside contextual studies

2.2. Eligibility Criteria and Selection Studies

This study included all study designs limited to studies published in English up to November 2024, covering all the period from the implementation of the first formal AQS globally to the present. The inclusion criteria were as follows:

- Studies proposing, modeling, or establishing criteria for altitude-adjusted AQS in outdoor air, considering any methodological approach.
- The primary pollutants (criteria pollutants) (Saxena and Sonwani, 2019) of interest included particulate matter, nitrogenous species, carbon oxides, and ozone.

2.3. Data Management

Relevant data were systematically and consistently collected from the selected studies. A standardized form was used to ensure uniformity in data extraction among reviewers. This form included specific fields to capture critical information such as study characteristics (author, year of publication, country of origin), study design, study population, contaminants criteria for AQS adjust and primary results or outcome measures.

Initially, two reviewers independently screened the information by titles and abstracts. If a decision could not be made based on theses, the full text of the article was reviewed. Any disagreements between reviewers were resolved by consensus or through the intervention of a third reviewer. The Rayyan QCRI web platform was used to manage the selection of articles, exclude duplicates, and record the reasons for exclusion, further ensuring the validity of our research.

3. Results

Our initial search identified a total of 2,974 articles, but 2,093 documents remained after removal duplicates. Following the titles and abstracts screening, 2,081 papers were excluded, leaving 12 articles for full-text evaluation as shown in Figure 1**Error! Reference source not found.**. A subset of 6 studies met the eligibility criteria and were included in the final review. The main exclusion reasons of studies were the lack of a clear proposal for AQS adjustment.

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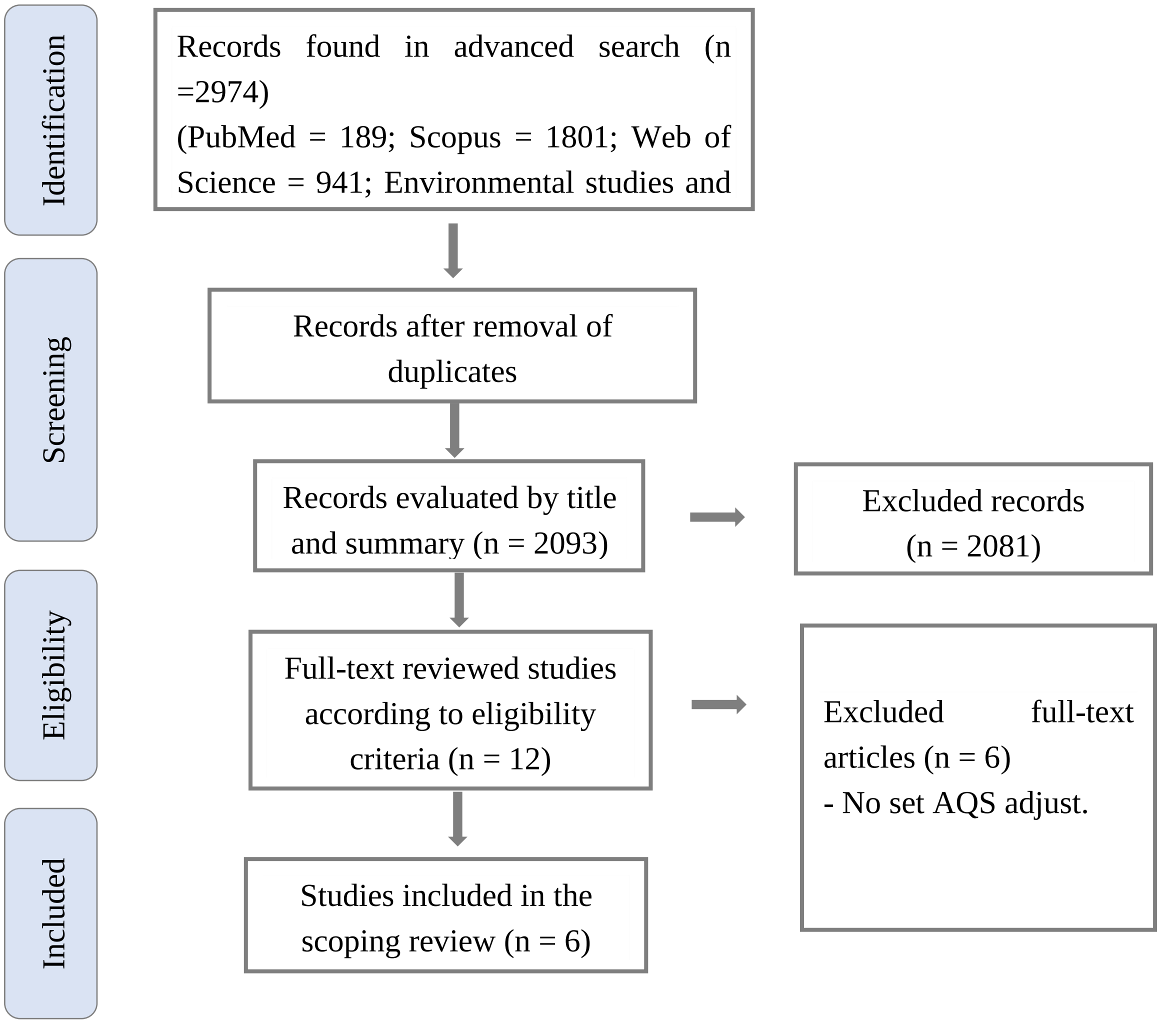

Figure 1. PRISMA Flowchart recommendations with reviewed information.

3.1. Altitude Adjusting Criteria in AQS

Six studies were identified that directly or indirectly address criteria for adjusting air pollutant standards based on altitude (Table 1). These studies fall into two main categories based on the variables and rationale underlying their adjustment models. The first category considers atmospheric and environmental factors, such as barometric pressure, temperature, and air density. The second focuses on human physiological adaptations to altitude, including changes in respiratory volume, hemoglobin-CO dissociation, and other physiological responses.

Table 1. Principles and model strategies for proposed AQS adjustment.

Author, year and country	**Addressed pollutant & Developed methodology**	**Rationale of proposed**	**Model calculation for AQS adjust**
Goddard and Goddard, 1979 USA-1979	• H_2S • Report with calculus.	Concentration conversion by change of pressure and temperature.	equivalent AQS $\frac{g}{m^3}$ = AQS $\left(\frac{\text{moles of air}}{m^3}\right)\left(\frac{\text{gm of pollutant}}{\text{mole}}\right)$

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Bravo and Urone, 1981- Mexico	• Particulate matter (PM_{10}, TPS) • Simulation	Hyperventilation at altitude increase risk of pollutant exposure.	$\text{Adjusted AQS} = \text{Sea level AQS}\left(\frac{\text{Standard respiratory rate}}{\text{Altitude respiratory rate}}\right)$
Collier and Goldsmith, 1983- USA	• CO • Simulation	Less oxygen partial pressure at altitude increases risk of carboxyhemoglobin	Coburn, Forster and Kane (CFK) Equation
Madueño et al., 2020 - Germany	• Black Carbon • Observational study. Measures in sample population	Hyperventilation at altitude increase risk of pollutant exposure	$\text{RDD} = \Sigma C_{ij} \cdot \text{MV}_i \cdot \triangle t_{ij}$ Where: C: concentration, MV: minute ventilation, △t: exposure time
Bravo Alvarez et al., 2013 - Mexico	• Particulate matter • Simulation	General gas law. Volume concentration change at different pressure and temperature	$\text{C}_\text{L} = \text{C}_\text{St} \cdot \left(\frac{\text{P}_\text{L}}{\text{P}_\text{ST}}\right) \cdot \left(\frac{\text{T}_\text{St}}{\text{T}_\text{L}}\right)$ Where: C: concentration, P: pressure, T: temperature. L: local and St: Standard
Yan et al., 2021 - China	• CO, NO • Observational study. Measures in field	Low oxygen content and ambient pressure can influence the vehicle pollutant emissions	$\text{f} = \left(\frac{\text{E}}{\text{E}_0}\right)$ Where: f is the altitude coefficient; E_o is the base emission factor and E is altitude emission factor

A pivotal early insight by Goddard and Goddard, 1979 proposed the application of altitude corrections to the California Ambient AQS. Their approach involved converting pollutant concentrations adjusted for pressure and temperature variations at specific altitude. They identified an 8% error lower in the AQS for hydrogen sulfide when comparing the standard at the time to its equivalent at an elevation of 2,200 ft (670.5 m).

The proposal by Bravo and Urone, 1981 highlighted altitude as a "*Fundamental Parameter*" for AQS adjustments, contextualized within the challenges posed by Mexico City, a congested capital city with elevation (2,240 m a.s.l.). The approach to adjusting AQS was rationalized based on the physiological implications of reduced barometric pressure and air density on gas exchange at the alveolar-capillary human lungs interface at HA. Under these conditions, lower airway resistance reduces respiratory effort, allowing a greater volume of air to enter the lungs compared to individuals at sea level (Cogo, 2011). Based on this premise, the authors proposed an AQS adjustment factor using the ratio between respiratory rates under standard and HA conditions in Table 1.

Using previous data on resting ventilation volume, body measurements, and average air particulate matter concentrations, they estimated that an average resident of Mexico City inhales an excess daily air volume of approximately 2,664 $L/m2$ of body surface area. This would correspond to an additional cumulative particulate matter exposure dose of 690 μg per square meter of body surface area.

Another notable physiological approach was proposed by Collier and Goldsmith, 1983, focusing on ambient carbon monoxide (CO) levels. It is well established that CO binds to hemoglobin (Hb) 200 to 300 times more strongly than oxygen (Patel et al., 2023), potentially leading to hypoxic effects (Kitagishi and Mao, 2021). The key assumption is that HA conditions would require stricter CO AQS due to the reduced partial pressure of oxygen (PO_2), which further enhances CO's affinity for Hb, resulting in higher carboxyhemoglobin (COHb) levels (McGrath, 1988).

The CO AQS stablished in U.S. set threshold at 10 $mg/m3$ (9 ppm) for an 8-hour exposure (U.S. EPA, 2024). However, the states of California and Nevada tightening it to 6 ppm (5.5 $mg/m3$) for the touristy Lake Tahoe Basin elevated at 1,900 m a.s.l (Tahoe Regional Planning Agency, 2021). In that context Collier and Goldsmith evaluated the appropriateness of these adjustments, with a theoretical mathematical model that integrated the relationships between O_2, CO, and Hb through the Coburn-Forster-Kane (CFK) equation, the Roughton-Darling equation, the oxygen dissociation curve (ODC), alveolar ventilation equations, and formulas for barometric pressure and pCO as functions of altitude (Collier and Goldsmith, 1983).

The CO AQS established in the U.S. sets a threshold of 10 $mg/m3$ (9 ppm) for an 8-hour exposure (U.S. EPA, 2024). However, California and Nevada tightened this limit to 6 ppm (5.5 $mg/m3$) for the Lake Tahoe Basin, a popular tourist destination located at 1,900 m a.s.l. (Tahoe Regional Planning Agency, 2021). In this context, Collier and Goldsmith assessed the appropriateness of these adjustments using a theoretical complex model integrating the relationships between O_2, CO, and Hb through the Coburn-Forster-Kane (CFK) equation, the Roughton-Darling equation, the oxygen dissociation curve (ODC), alveolar ventilation equations, and formulas for barometric pressure and pCO as functions of altitude.

The model's results indicated that the 8-hour and 1-hour CO standards established for sea-level conditions would not require modification to ensure health protection at HA, provided if the standards were expressed in volumetric terms. This contrasted with the EPA´s approach, which was based on gravimetric measurements. The rationale behind this finding was that altitude and hyperventilation proportionally decreases both inspired pCO and pO_2, maintaining their relative balance (Savioli et al., 2022). However, it was mentioned that other factors not considered, such as increased CO emissions due to inefficient vehicle engine combustion at altitudes, could heighten exposure risks (Jiang et al., 2025).

An indirectly adjusted measure included in this review is the study by Madueño et al., which examines black carbon (BC) exposure at HA (Madueño et al., 2020). The authors estimate the potential Respiratory Deposited Dose (RDD) of BC in individuals using different modes of transportation in La Paz and El Alto, Bolivia—cities located at 3,600 and 4,100 m a.s.l., respectively. The study compares RDD findings with similar research conducted in low-altitude regions, revealing that black carbon exposure while walking in Bolivia is, on average, 2.6 times higher than at sea level.

The primary factor for calculating RDD in Table 1 is the minute ventilation rate (MV) associated with a given activity, commonly referred to as the inhalation rate (Horiuchi et al., 2019). MV should be considered the key variable in assessing exposure under the same air pollutant concentration (Dons et al., 2012; Milledge, 1968). Based on these findings, the authors highlight the urgent need for stricter and more aggressive policies and regulations on road emissions in HA cities (Madueño et al., 2020).

Among the studies that adopt environmental and atmospheric approaches to altitude-based AQS adjustments, Bravo Alvarez et al., 2013 is one of the most frequently cited on this topic (Feng et al., 2022; Liu et al., 2021; Torres-Duque et al., 2024). Their approach is based on a straightforward application of the general gas law equation, proposing an adjustment factor derived from the ratio of temperature at sea level (298.15 K) to its corresponding value at a given altitude (T_L), multiplied by the ratio of atmospheric pressure at that altitude (P_L) to its standard sea level value (1013 hPa) in **Table 1.**

This is a simple but versatile model that can be applied to any AQS pollutant. The study exemplifies its application by adjusting the Mexican AQS for total suspended particles (TSP) and particulate matter less than 10 μm (PM_{10}) across cities at different altitudes in Latin America (Bravo Alvarez et al., 2013). The specific correction factors for PM_{10} ranged from 0.97 for Santiago de Chile (567 m a.s.l.) to 0.68 for El Alto, Bolivia (4,050 m a.s.l.), indicating that as altitude increases, AQS values may be proportionally reduced. Among the Latin American cities analyzed were Mexico City (Mexico), with a factor of 0.79; Bogotá and Cali (Colombia), with 0.76; Quito (Ecuador), with 0.75; and Cusco (Peru), with 0.70.

The last study was conducted by Yan et al., 2021, focusing on air quality HA road tunnels. The current Chinese guidelines for tunnel ventilation (China, 2014) recognized the influence of altitude on exacerbated vehicle CO emissions. To address this effect, the guidelines establish a CO altitude emission coefficient, which quantifies the additional emissions produced at a given altitude compared to the same vehicle operating at sea level. According to these regulations, the CO emission coefficient under standard conditions (below 400 m a.s.l.) is set at 1, but it triples at an altitude of 4,000 m (China., 2014).

Yan et al., 2021 aimed to assess the validity of the existing CO altitude emission coefficient and to propose a similar coefficient for NO, which was not included in the guidelines. They measured CO and NO levels in four road tunnels at altitudes ranging from 500 to 3,850 m a.s.l., considering atmospheric parameters, traffic conditions, and structural characteristics. Using mass balance models, they calculated emission factors and found that the CO altitude coefficient increases nearly linearly with altitude, aligning with the values established in the guidelines within the studied altitude range. Additionally, they proposed a NO emission coefficient of 0.403 $g \cdot vehicle^{-1} \cdot km^{-1}$ at 500 m, which increases linearly to 0.886 $g \cdot vehicle^{-1} \cdot km^{-1}$ at 3,850 m a.s.l.

3.2. Altitude Influenced Pollutants AQS and Regulation in Major HA Countries

The implementation of AQS levels varies significantly across countries, with differing levels of stringency in pollutant thresholds, leading to a wide range of regulations for the same pollutant (Nazarenko et al., 2021). This variation has been attributed to multiple factors and their interrelations, including government systems, a country's level of development, sociolegal cultures, technical expertise, historical patterns of air quality legislation, and other considerations (UNEP, 2021). However, specific conditions such as topography and altitude are often either overlooked or insufficiently addressed

The WHO AQS (2000) guidelines acknowledge altitude as a factor influencing air pollutant concentrations; however, they do not provide specific recommendations for addressing altitude-related AQS adjustments considerations (WHO, 2000). Growing evidence with strong theoretical plausibility supports the impact of altitude on pollutant concentrations, particularly for ozone (O_3), nitrogen oxides (NO_x), and particulate matter (PM) (Ning et al., 2018, 2024a; Wang et al., 2024). These criteria pollutants are of major public concern, with $PM_{2.5}$ being the leading contributor to global morbidity and mortality (Kim et al., 2015; Silva et al., 2013), and O_3 ranking as the second most detrimental pollutant to human health (Ebi and McGregor, 2008).

The magnitude effects and outcomes are determined by the absolute altitude. According to the EPA, at elevations above 1,500 m, significant atmospheric changes begin, with pressure decreasing by approximately 15% compared to sea level (U.S. EPA, 1978). HA is defined as elevations between 2,500 and 3,500 m a.s.l. (US standard Atmosphere, 1976), while very high altitude (>3,500 m) presents extreme conditions that exacerbate the impacts of various risk factors (Burtscher, 2013). To evaluate current air quality legislation and specific regulatory approaches in countries where a significant proportion of the population resides above 3,500 m a.s.l. (**Fig. 1**), we examined national AQS frameworks from China, Peru, and Bolivia. Our analysis focuses on their regulatory standards for PM, O_3, and NO_2 (Table 2)

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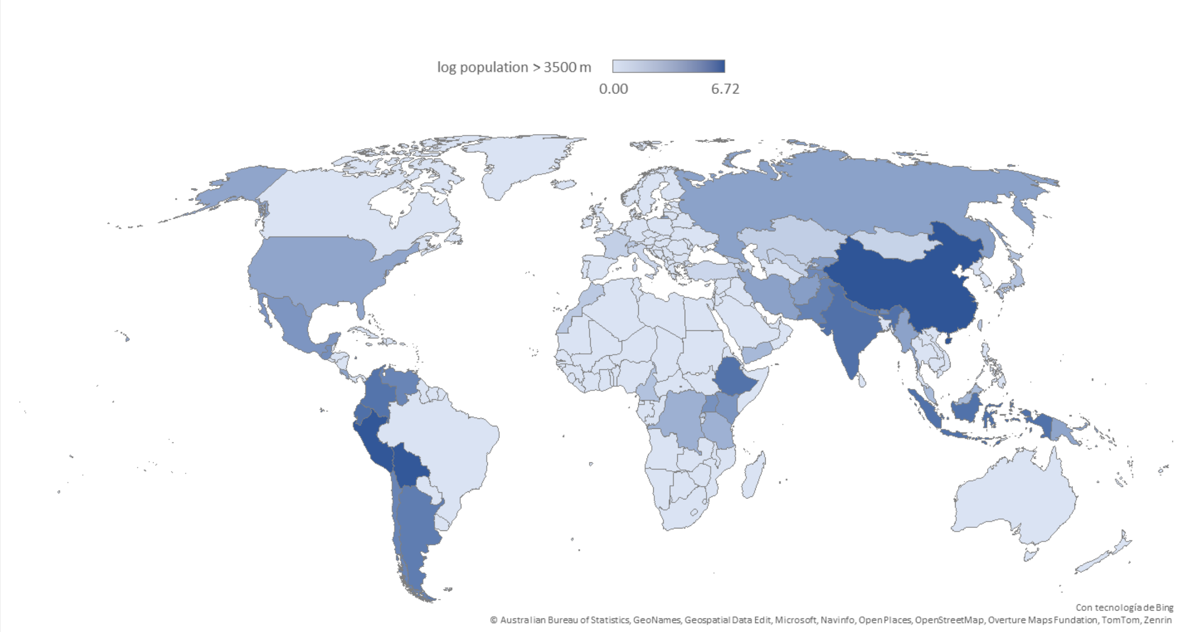

Figure 1. Global distribution of population living at altitudes ≥3,500 m (log_{10} scale). The three countries with the largest populations at this altitude are China, Peru, and Bolivia. Data sourced from Tremblay and Ainslie, 2021..

Table 2. Particulate matter AQS for countries with larger population living in altitude above 3500 m a.s.l.

		Bolivia		Peru	China	
Contaminant	**Average time**	**Permissible Air Quality Limits[1]**	**Maximum limits for atmospheric pollutants [2]**	**Air Quality Standards[3]**	**Ambient air quality standards [4]**	Guide WHO 2021
$PM_{2.5}$, µg/m³	Annual	--	10	25	Class I: 15 Class II: 35	5
	24 hours	--	25	50	Class I: 35 Class II: 75	15
PM_{10}, µg/m³	Annual	50	20	50	Class I: 40 Class II: 70	15
	24 hours	150	50	100	Class I: 50 Class II: 150	45
Total suspended particles, µg/m³	Annual	75	75	--	--	--
	24 hours	260	--	--	--	--
Ozone, $ug/m3$	1 hour	236	--	--	Class I: 160 Class II: 200	--
	8 hours	--	100	100	Class I: 100 Class II: 160	100
	Annual	--	60	--	--	--
NO_2 µg/m³	1 hour	400	200	200	200	--
	24 hours	150	150	--	80	25
	Annual	---	40	100	40	10

[1] Regulations on Air Pollution. Environmental Law No. 1333, [2] Bolivian Standard NB 62011:2018, NB 62014:2018 and 62018:2018 of IBNORCA, [3] Ministerial Resolution No. 94-2017-MINAM, [4] GB 3095-2012 standard.

China has the largest HA population globally, with 5.1 million people residing above 3500 m a.s.l., primarily due to the inclusion of the Tibetan Plateau, the highest landmass on Earth (Wu, 2001). However, this represents only a very small fraction—0.37%—of the country's total population (Tremblay and Ainslie, 2021). China's current national AQS (GB 3095-2012) were issued by the

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Ministry of Environmental Protection in 2012 for primary pollutants and came into effect nationwide in January 2016 (Wang et al., 2023). Since then, air quality in China has steadily improved due to the implementation of various national policies prioritizing clean air targets (Zhao et al., 2020).

A distinctive feature of China's AQS is its dual-level system, which establishes two classes of limit values for each pollutant. Class I standards apply to areas requiring special protection, such as scenic spots and nature reserves and class II standards for all other areas, including residential, mixed-use, industrial, and rural zones. The annual mean $PM_{2.5}$ concentration limit across mainland China is set at 35 $\mu g/m3$. Compliance with this standard has been relatively high; in 2022, only 18% of cities (primarily in the north, central regions, and the Sichuan Basin) recorded annual mean $PM_{2.5}$ concentrations exceeding the national ambient AQS (Zhang et al., 2023).

Despite these efforts, China's air quality standards (AQS) for particulate matter pollutants remain less stringent than the WHO air quality guidelines (WHO, 2021). Additionally, the 8-hour ozone AQS level (Class II) is the most lenient among the countries analyzed in this review. According to national regulations, provincial governments in China may establish local AQS for parameters not covered by national standards and impose stricter limits on those already regulated. For instance, Song et al. proposed adjustments for Hainan Province (Song et al., 2024), and administrative division adjustments (ADA) have been suggested to modify environmental governance policies for local governments (Feng et al., 2022). However, there is limited literature on the development of local AQS for HA cities in China (Wang et al., 2023).

The spatiotemporal distribution of air pollution indicates low pollution levels in the peripheral areas of HA zones (Ning et al., 2018), likely due to the sparse population and minimal industrial activity in these regions. However, seasonal pollution spikes can occur, as observed in Lhasa, one of the highest cities in China (3,650 m). While the annual average $PM_{2.5}$ concentration remains within the Chinese standard of 35 $\mu g\, m^{-}3$ (Li et al., 2016), winter pollution is severe. This is primarily attributed to the widespread use of butter lamps, which significantly increase $PM_{2.5}$ levels, raising the city's average winter concentration to 118 ± 60 $\mu g\, m^{-}3$ (Li et al., 2019).

Peru ranks second, with an estimated 4 million people living above 3,500 m a.s.l., although this figure is likely underestimated due to a lack of comprehensive data (Tremblay and Ainslie, 2021). The HA Peruvian population is primarily distributed along the Andean Cordillera in western South America. After Chile, Peru has the largest proportion of its territory covered by the Andes (CONDESAN, 2012), a region rich in mineral resources that has driven large-scale displacement of households and communities (Bury, 2007; Velásquez, 2013). Notably, the highest-altitude city in the world is the Peruvian mining settlement of La Rinconada, located between 5,100 and 5,300 m, where gold mining activities are predominant (Hancco et al., 2020). Another notable city is La Oroya (3,745 m), which has been ranked among the ten most polluted places on Earth. An international court has even assessed the state's responsibility for the severe air contamination affecting its population (Neumann, 2016; Spieler, 2010).

Peru's AQS, established in 2017, align with the WHO Interim Target I (2005) for PM pollutants (World Health Organization., 2006). According to air quality monitoring data from Peru, the $PM_{10}/PM_{2.5}$ ratio for a 24-hour period ranges between 0.32 and 0.65, consistent with the suggested value of 0.5 for developing countries (Moore, 2001). In the case of NO_2, the annual AQS is higher than in other countries and exceeds the WHO recommendation by a factor of ten (**Table 2**). Currently, there is no specific AQS regulation for HA cities. However, a legislative proposal introduced in 2016 (Draft Law 756/2016-CR) suggested an adjustment model for AQS regarding PM, NO_2, O_3, and SO_2, incorporating correction factors based on air density and atmospheric pressure at each measurement altitude (Villanueva Mercado, 2016). As of this review, no further discussion on its implementation has taken place.

Bolivia has the highest proportion population living above 3,500 m, approximately 32.6% of its total habitants (Tremblay and Ainslie, 2021). Additionally, is there the highest capital city in the world (La Paz, 3869 m average elevation). As characteristic of metropolitan areas, the vehicular emissions represent an important contributor to its air pollution (Mardoñez et al., 2023). Cochabamba (2.558 m) Bolivian city was listed by WHO as one of the five most contaminated cities in Latin America (UNEP,

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2016). This due to its complex 'bowl' topography which influencing accumulation of air pollution associated to the transport emissions (Pareja et al., 2011).

AQS regulation presents a unique case, operating under two frameworks: the official 1992 General Environmental Law (N° 1333) and the Bolivian technical standards (*Normas Bolivianas*, NB) issued by IBNORCA (Bolivian Institute of Standardization and Quality). The latter is indicated only as a reference guide, without mandatory enforcement. Notably limits for $PM_{2.5}$, are absent in the General Law and the PM_{10} and $PM_{2.5}$ limits set by IBNORCA are among the most stringent compared to other countries and are remarkably close to the WHO air quality guidelines (**table 2**). The specific reasons for this significant difference remain unclear, and it is uncertain whether they are related to the altitude conditions. In contrast, the General Law establishes the most lenient AQS, with the highest limits for PM_{10}, O_3, and NO_2 (1-hour standard).

4. Discussion

This review assesses the available scientific evidence on the criteria and models proposed for adjusting air quality standards (AQS) in response to altitude conditions, alongside an analysis of air quality regulations and policies implemented in countries with significant populations residing above 3,500 m a.s.l.

Globally, epidemiological studies evaluating health risks associated with pollutant exposure in HA urban populations remain scarce (Ning et al., 2024b; Vilcassim and Thurston, 2023). Air quality monitoring and regulatory efforts have traditionally focused on major metropolitan areas, predominantly located at or near sea level (Carvalho, 2016). Consequently, recommendations, regulations, and international guidelines are largely derived from studies conducted in these settings (WHO, 2021). This knowledge gap may stem, at least in part, from the longstanding perception that HA environments inherently offer fresher and cleaner air due to lower population density and limited industrial activity (Zhang et al., 2018). However, several HA urban centers have undergone significant development, disrupting environmental equilibrium through increasing emissions that pose substantial public health challenges (Dame et al., 2019; Luan and Li, 2021). Furthermore, these challenges may be exacerbated by climate change and urban expansion, as HA environments could become increasingly sought after as refuges from extreme heatwaves (Asad et al., 2023; Ding et al., 2021).

This review identifies six proposals for adjusting AQS, which can be categorized into two distinct groups based on their underlying principles. Three of these proposals primarily focus on atmospheric and external conditions, while the remaining three emphasize human physiological responses. In the first group, both Goddard and Goddard, 1979 and Bravo Alvarez et al., 2013 proposed a similar approach based on the relationship between pollutant concentration, pressure, and volume. This reasoning suggests that AQS—expressed as pollutant concentrations under standard reference conditions (25°C and 760 mmHg at sea level)—would inherently yield lower converted concentrations at higher altitudes. A comparable concept was explored by Warthon Ascarza, 2023 in their doctoral thesis, incorporating an exponential function to adjust PM AQS according to altitude. The adjustment factor estimated for Cusco (0.67) closely aligns with that reported by Bravo (0.70) for the same city, providing empirical support for this method. However, the validity of this approach remains debated, as it relies on the assumption of ideal gas behavior according to theoretical gas laws (Woody, 2013), which may be oversimplified given the complex interactions in real-world atmospheric conditions.

Yan et al., 2021, for its part, conducted an observational study examining variations in vehicle CO and NO emissions in HA tunnels. Multiple studies have reported that tailpipe emissions tend to increase under these conditions due to the diminished performance of internal combustion engines (Giraldo and Huertas, 2019; Martínez et al., 2022). The primary factors contributing to this phenomenon include lower ambient temperatures and reduced oxygen availability, both of which negatively impact fuel combustion efficiency (Bishop et al., 2001). Since most engines are calibrated in standard factory settings at sea level, their performance deteriorates at high altitudes, leading to higher fuel consumption and increased pollutant emissions (Qi et al., 2023). In this context, regulations focus on a specific microenvironment by incorporating an emission coefficient, which

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plays a crucial role in infrastructure ventilation and air quality management in road tunnels, as seen in China (China., 2014).

The second group shifts the focus to human physiological responses to altitude. Bravo and Urone, 1981 and Madueño et al., 2020 incorporated respiratory variables into their calculations to account for differences in the volume of air inhaled, which serves as a proxy for pollutant intake. Bravo and Urone, 1981 used ventilation volume measurements expressed as daily air intake per unit of body surface area, while Madueño et al., 2020 employed a more recent variable—minute ventilation—as a refined approach to quantify respiratory differences (Borghi et al., 2021). In these cases, the ratio or difference between observed measurements in both representative populations provide a feasible factor for adjusting AQS.

Evidence supporting these physiological adjustments in high-altitude environments has been explored. In vitro respiratory tract models have demonstrated that increasing altitude significantly enhances the deposition of inhaled particles in the respiratory system (Li et al., 2024), making it more vulnerable and less capable of effectively expelling harmful substances (Wuyam et al., 2022). The natural physiological response to altitude is known as the hypoxic ventilatory response (HVR), which triggers an increase in breathing to enhance alveolar ventilation—by up to fivefold in newcomers to HA environments (Grimminger et al., 2017). However, distinct respiratory patterns are observed among native high-altitude populations. Tibetans exhibit high resting ventilation and a strong HVR, similar to acclimatized lowlanders, whereas Andeans tend to have lower resting ventilation and a blunted HVR (Slessarev et al., 2010). Despite these differences, several studies consistently report higher spirometry values in HA populations (Greksa et al., 1988; López Jové et al., 2018; Weitz et al., 2016).

Finally, Collier and Goldsmith, 1983 examined the complex relationship between altitude and CO-Hb binding. Although their calculations did not provide sufficient evidence to justify adjusting CO AQS in volumetric terms, they estimated that exposure to 8 ppm of CO would result in equilibrium COHb levels of 1.4% at sea level and 1.8% at 3,579 m. This finding highlights an increase in COHb levels at altitude, even in the absence of ambient CO, in accordance with Haldane's principle (Teboul and Scheeren, 2017). CO toxicity primarily causes damage through anoxic injury and lipid peroxidation. At high altitudes, this condition can be potentially fatal, as it clinically mimics acute mountain sickness (AMS). Several reports have documented CO-related fatalities in tents at high altitudes due to poorly ventilated spaces and low-flame camping stoves (Leigh-Smith, 2004). However, such cases appear to be underreported due to the overlap between CO toxicity symptoms and AMS, as well as the lack of definitive diagnostic testing (Foutch and Henrichs, 1988).

Current air quality regulations in the Lake Tahoe Basin, Nevada (1,900 m a.s.l.), enforce stricter thresholds compared to the U.S. National Ambient Air Quality Standards (NAAQS) (Tahoe Regional Planning Agency, 2021). Notably, this is the only policy explicitly based on altitude conditions that we identified. In contrast, Denver, CO (1,600 m a.s.l.) adheres to the CO NAAQS of 9 ppm, a limit that is frequently exceeded during the winter months (Crow, 1979).

The complex interplay between atmospheric physics and human biology at high altitudes underscores the need to discuss potential adjustments to AQS for effective public health protection and air quality monitoring. AQS serves as the core strategic framework for ambient air quality management worldwide, forming the foundation of environmental protection efforts and a key regulatory tool. If AQS are designed primarily to safeguard human health, then physiological respiratory adaptations could provide one of the most relevant approaches for studying long-term exposure risks. This perspective aligns with the methodologies adopted by international air quality guidelines (WHO, 2021).

Models that adjust AQS based on environmental variables can be refined through monitoring systems, such as gravimetric methods for particulate matter collection. The rationale behind this approach is that, even if a fixed threshold is maintained, actual pollutant concentrations may or may not exceed it depending on local pollution levels. This can be verified through environmental monitoring, which already incorporates altitude adjustment protocols. However, developing a comprehensive framework that integrates both environmental and physiological considerations remain a complex challenge.

The rationale for adjusting or normalizing AQS based on altitude is supported by diverse, yet still limited, evidence (U.S. EPA, 1978). Recent studies on new particle formation (NPF) have observed that nucleation processes occur more frequently at high altitudes (Boulon et al., 2011; Venzac et al., 2009) , particularly in the Southern Hemisphere (Sellegri et al., 2019). NPF is a major source of atmospheric ultrafine particles (<100 nm), contributing to approximately 50% of aerosol number concentrations in the troposphere (Spracklen et al., 2008). Additionally, intense solar radiation (UV <410 nm) at high altitudes plays a direct role in accelerating tropospheric O_3 formation (Yu et al., 2021) through the photodissociation of NO_2. This process exhibits an altitude-dependent response, with ozone levels increasing by 21% to 70% at 1,000 m a.s.l. (108). Other environmental factors include the increased occurrence of prolonged thermal inversion events and the influence of topographical features that restrict pollutant dispersion (Nejad et al., 2023).

In the pursuit of tailored air quality regulations for countries with a significant portion of their population residing at very high altitudes (>3,500 m a.s.l.), the most concentrated regions are the Qinghai-Tibet Plateau in Asia and the Andes in South America. These two areas serve as major high-altitude population hotspots, accounting for at least 80% of the world's inhabitants living at such elevations (Tremblay and Ainslie, 2021). Despite these unique environmental conditions, no specific regulations have been identified that explicitly account for altitude or topography in AQS adjustments for high-altitude urban areas. Notably, Bolivia lacks $PM_{2.5}$ regulations, despite the country's inherently high-altitude setting, highlighting a critical gap in air quality management.

Despite the novelty of this finding, the results are limited by the small number of available studies and the methodological heterogeneity among them. This highlights an important research gap, but also reflects a scientific challenge rooted in the geographically disproportionate nature of high-altitude exposure. Nonetheless, this work outlines the dual-faceted approach needed to adapt AQS to the unique conditions of HA environments.

5. Conclusions

This scoping review provides the first comprehensive assessment of criteria and models proposed for adjusting AQS in altitude environments, systematically identifying and categorizing these approaches. By expanding existing knowledge, this research offers a valuable framework for future studies aimed at developing robust, evidence-based AQS tailored to the unique challenges of HA regions.

The complex interplay between atmospheric, environmental, and physiological factors highlights the need for continued discussion on AQS adjustments to strengthen public health protection and monitoring. While air quality policies have contributed to pollution reduction in some areas, achieving truly safe air quality standards remains a significant global challenge.

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