

Article

Environmental Governance and Gender Inclusivity: Analyzing the Interplay of PM2.5 and Women's Representation in Political Leadership in the European Union

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Abstract: This research addresses a critical gap in the literature by establishing a direct correlation between particle pollution from fine particulates (PM2.5) and women's political participation. It offers a nuanced understanding of gender dynamics in governance and their impact on environmental outcomes. Focusing on 27 European Union (EU) countries from 2013 to 2021, econometric techniques unveil common trends, underscoring cross-sectional dependence. This study reveals distinct gender behaviors in combating pollution, with women in parliaments and regional assemblies notably contributing to pollutant reduction. However, the negative impact of women's engagement in politics on PM2.5 intensifies the lower part of the representation hierarchy. Policymakers are urged to create conditions fostering women's political participation, advocating for gender quotas to address underrepresentation. The research emphasizes the interconnectedness of gender, politics, and environmental issues, urging heightened awareness among policymakers. Limitations include a confined scope and duration, requiring cross-validation beyond the EU. Future research pathways involve exploring the intricate connections between gender, politics, and environmental initiatives, seeking thresholds for impactful women's representation. In contributing to Sustainable Development Goals (SDGs), this study aligns with SDG 5 (gender equality), SDG 3 (good health and well-being), SDG 7 (affordable and clean energy), SDG 11 (sustainable cities and communities), SDG 16 (peace, justice, and strong institutions), and SDG 17 (partnerships for the goals).

Keywords: gender; politics; air pollution; PM2.5; sustainable development goals; gender equality; environmental governance; women's representation; policymaking



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1. Introduction

Do more women in political bodies lead to better air to breathe? By examining the uniform and dissected effects along the quintile axis of representation and level of political hierarchy, this study establishes new evidence for the effects of women in politics on PM2.5.

1.1. Background

Despite ongoing improvements, air pollution is a major cause of disease and mortality in Europe, killing 253,000 prematurely [1–3] or, in comparative terms, approximately equivalent to the entire female population of Bratislava every year [4]. Air pollution and economic growth have a strong long-run relationship [5], and despite the forecasted weak medium-term economic growth in the European Union, air pollution still needs addressing to curtail its negative effects now whilst transitioning to a green economy, which itself

can accelerate growth [6]. As economic and environmental aspects can go hand in hand, addressing the negative effects of air pollution is especially important.

Of all air pollutants, the most severe impacts on health are attributable to fine particulate matter (PM_{2.5}), a mixture of solid particles and liquid droplets, all of which are around 30 times smaller than a human hair [7]. To be more precise, PM_{2.5} is defined by the United States Environmental Protection Agency [7] as fine inhalable particles with diameters of 2.5 µm or less, and their main emitters are agriculture, industry, transport, buildings, and energy [8]. In particular, primary particles come from metallurgical and combustion, and secondary particles result from atmospheric reactions; less is known about deposited and resuspended fine particles [9]. Solid fuel combustion is responsible for almost half (45%) of primary PM_{2.5} [1]. Not all sources contribute to PM_{2.5} evenly [10]: in Europe, fuel oil combustion, traffic non-exhausts, and soil dust vary with site location (high traffic versus rural), while the burning of biomass, sea salt, and traffic exhausts is relatively homogeneous across sites [11].

Regarding the detrimental health effects, these particles shorten life expectancy from 1 month to 1.5 years in Europe [12] in the long term, but in the short term, elevated PM_{2.5} concentrations from the previous day are associated with 0.8% excess all-cause mortality [13], making fine particulate matter especially worthwhile to study.

1.2. Environmental Policies in the European Union

The sources of air pollution are major contributors to climate change [5]. More specifically, the emissions of pollutants, such as PM_{2.5}, trap heat in the atmosphere, exacerbating climate change, including the rise of temperatures and changes in the amount of precipitation [14]. Despite its adverse effects on climate change, PM_{2.5} is also identified as one of the major drivers for biodiversity loss [8], the most harmful air pollutant for human health [2], and the most complex pollutant to manage locally [15]. Health risk reduction and clean air reduce pressure on ecosystems [16] and align with European Green Deal policy objectives. As a result, the deaths attributed to PM_{2.5} serve as a proxy for pollution in the legally binding European Commission's zero pollution action plan [17]. Moreover, the Ambient Air Quality Directives—setting air quality standards and committing to emission reduction within the EU, along with emission standards for key sources [16]—are supplemented by the UNESCO Air Convention, aiming for transboundary emission reduction. The European Commission aims to cut air pollution's health effects significantly, targeting a minimum 55% reduction in premature deaths linked to PM_{2.5} by 2030, relative to figures from 2005, as part of its zero-pollution action plan [2]. However, controlling PM_{2.5} requires a broad policy, including various pollution control measures, to be effective [18].

Conversely, climate change also affects air pollution, as changes in meteorological conditions that are predicted to accelerate in decades to come [14] can hinder the natural dispersion and removal of air pollutants, intensifying problems related to air quality [19]. According to the World Health Organization, climate change is also identified as one of the most hazardous phenomena to human health [20]. In order to overcome this serious problem, the European Commission introduced the EU Strategy on Adaptation to Climate Change alongside the European Green Deal Communication in 2021, pledging to enhance the adaptability and climate resilience of health systems across the EU and its member states. Furthermore, to address climate change, two key approaches are employed: (i) mitigation strategies, which involve reducing greenhouse gas emissions and removing these gases from the atmosphere, and (ii) adaptation strategies, which entail implementing measures to minimize the effects of climate change [21]. These strategies are complementary, as effective mitigation can decrease the necessity and expense associated with adaptation efforts.

1.3. Gender Disparities in Political Leadership

There are now more women in political leadership at both national [22] and European levels, and this trend has persisted across generations [23,24]. Moreover, these women are substantively representing the voice of women [22]. However, descriptive representation

on national and European levels still varies due to differences in national political culture, rules, and the gatekeeper role of political parties [23].

Gender parity has been promoted through electoral quotas (reserved seats, candidate quotas, or voluntary political party quotas) in most European countries [25]. Nevertheless, high female representation has been found to negatively affect substantive representation by male members of parliament [26]. The expectation is that gender parity across the political preference spectrum will expand as women increasingly align with left-wing ideologies in Europe [27], historically being more likely to be appointed ministers by left-wing parties [28].

1.4. Policies Promoting Gender Equality

As a fundamental right within the EU, gender equality is promoted through legislation (six directives) and jurisprudence, and the Gender Equality Strategy is implemented by targeted measures and gender mainstreaming [29]. Commitment to the Beijing Declaration and UN Sustainable Development Goals also delineate political decision-making within the EU. Regarding leadership in politics, the EU Platform for Diversity Charters facilitates the exchange of good practices [29], and current regulation proposals include making European political party funding more transparent [30].

1.5. Existing Studies on the Interplay of PM2.5 and Women's Representation

As discussed previously, there is a lack of academic literature linking PM2.5 and women's political representation. To our knowledge, the closest linkage examined is the effects of women's political status on life satisfaction [31], whereby countries with high satisfaction levels tend to have low pollution levels [32]. A broader branch of the literature explores the relationship between economic and demographic markers and air pollution: younger and less educated people are more exposed to fine particles, and occupation strongly influences exposure [33]. Regarding inequality trends, areas experiencing an increase in the ethnic majority traits of the population correlate with improvements in air quality [34,35]. More abstractly, political power is selfishly used to set environmental public good extraction levels, and introducing a voting quota enhances socially preferred environmental regulation [36].

To bridge this gap, we inquire whether there is a linkage between air quality and the representation of women in political leadership roles (see Figure 1 below).

This investigation examines representation at government, parliament, and regional assembly levels in a cross-section and across 2013–2021 (see Figure 2 below).

This investigation embarks on a pioneering exploration of the intricate relationship between political determinants, gender, and environmental outcomes, following an interdisciplinary approach. This holistic perspective departs from traditional studies that often focus on individual components in isolation. By integrating these diverse aspects simultaneously, this investigation aims to provide a more comprehensive understanding of the dynamics influencing air pollution and underscore the importance of considering diverse perspectives in shaping policies that effectively combat air pollution.

Moreover, this research explores the relationship between political determinants and air pollution, particularly concerning the diverse interests held by minority and under-represented groups, given that protecting the environmental public good is an ecological concern and a social justice imperative. These groups, therefore, possess unique incentives to either endorse or legislate for the protection of the environmental public good. Then, elucidating this connection, this study aims to provide a comprehensive understanding of how to align policies not only for gender parity but also for fostering clean air for the different communities within the European Union.

In the following section, this paper provides a comprehensive overview of the past literature, data research, and methodologies employed. Section 3 presents the data and method applied. Section 4 delves into the empirical findings, and the implications of these

results are explored in Section 5. This paper concludes with Section 6, highlighting valuable policy insights from this study's outcomes.

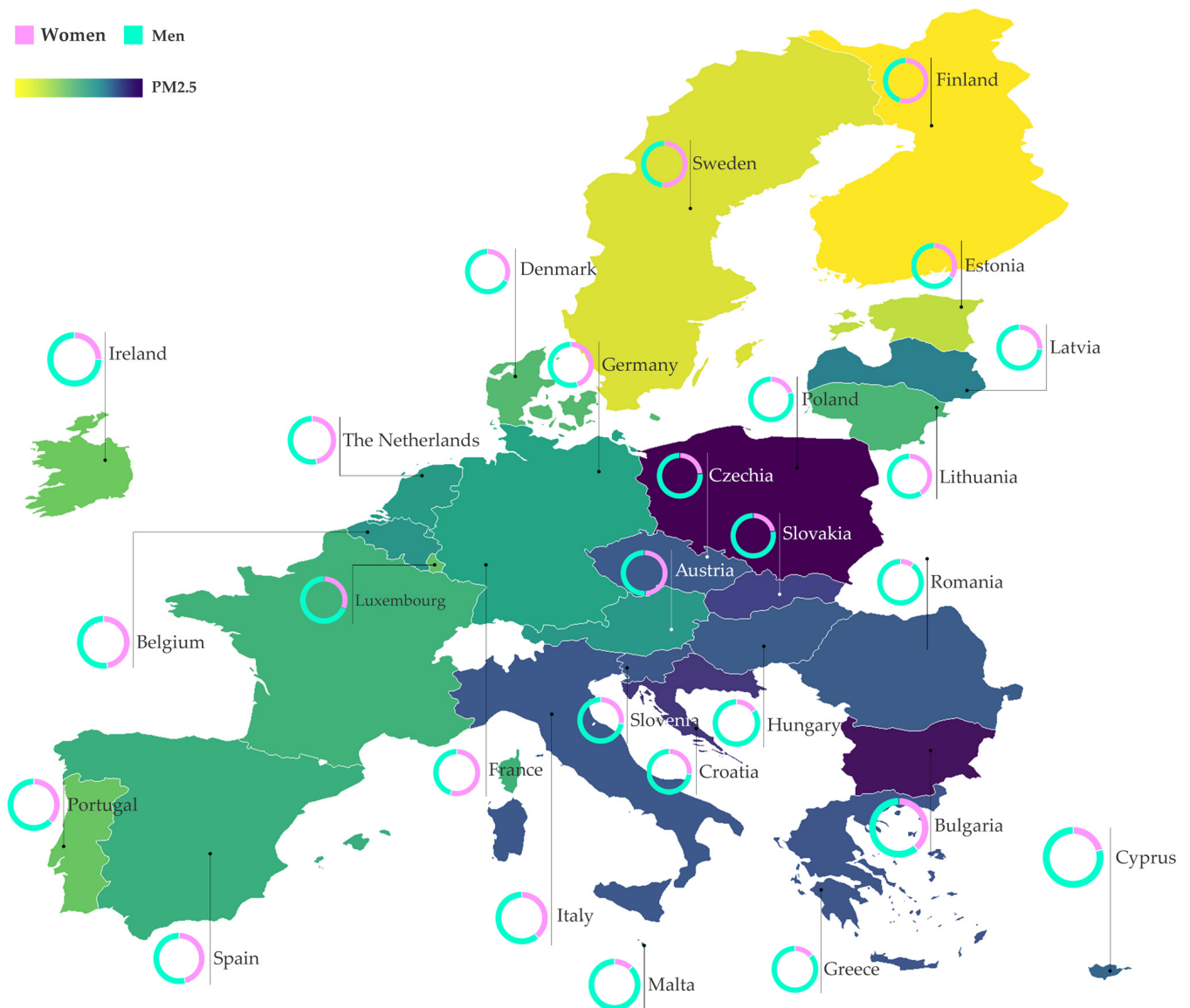


Figure 1. Percentage of women holding positions as members of ministries and PM2.5 levels in the EU-27. Please note that the PM2.5 data are for 2020, while the women's representation data are for 2021. This graphic was generated using information from OECD data [37] and the European Institute for Gender Equality (EIGE) [38].

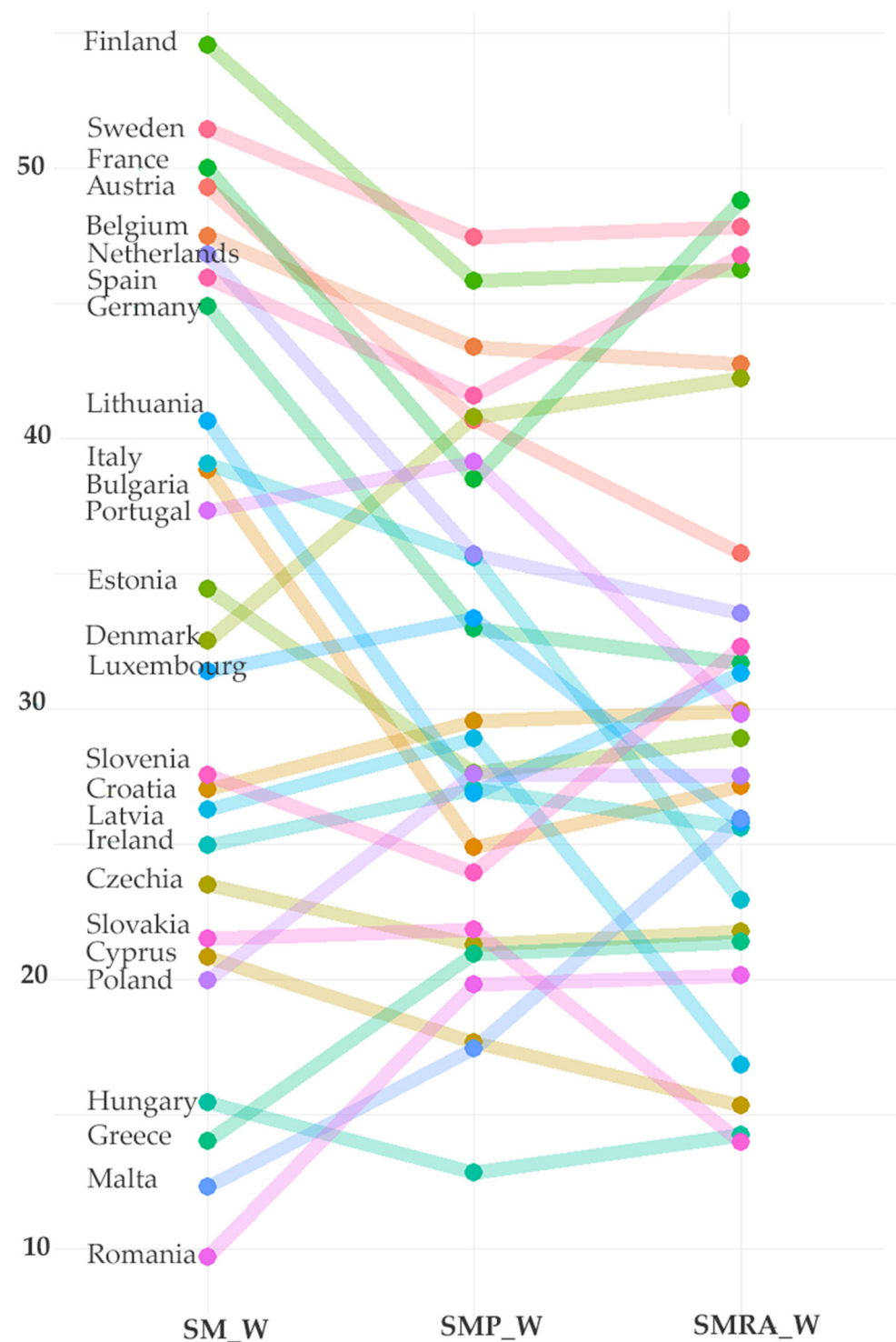


Figure 2. The representation of women in leadership roles in the EU-27 in 2021, categorized by leadership levels. Notes: SM_W indicates representation as ministers, SMP_W indicates representation as members of parliament, and SMRA_W indicates representation in regional assemblies. This visual was created using data from the European Institute for Gender Equality (EIGE) [38].

2. Literature Review

The literature review for this study will be divided into subsections addressing the intersections of environmental and gender issues, the gendered impacts of environmental policies, the effects of environmental problems on political engagement, exist-

ing studies on the interplay of PM_{2.5} and women's representation, and the respective conceptual framework.

2.1. Intersections of Environmental and Gender Issues

The text discusses the interconnectedness between climate change and air pollution, highlighting their shared causes and solutions. It mentions that air pollution exacerbates climate change by releasing greenhouse gases and particulates from various sources such as traffic, industry, and domestic burning. Specifically, vehicle emissions, industrial activities, and household fuel combustion contribute significantly to pollution levels in urban environments. These pollutants trap heat in the atmosphere, leading to global warming. On the other hand, climate change can also worsen air pollution by altering weather conditions and hindering the natural cleansing of pollutants from the air. For example, changes in temperature and precipitation patterns can increase the frequency and intensity of wildfires and dust storms, resulting in higher levels of toxic pollutants and the formation of secondary pollutants, particularly in conditions of high temperature and low rainfall.

Considering the previous harmful facts, the concept of 'environmental justice' arose in the literature, and the United States Environmental Protection Agency defined that as 'the fair treatment and meaningful involvement of all people regardless of race, colour, national origin, or income concerning the development, implementation, and enforcement of environmental laws, regulations, and policies' [39]. This concept directly refers to distributional justice, which includes equal access to natural resources and environmental services like clean water or protection from environmental degradation such as deforestation or air pollution [40]. Moreover, environmental justice encompasses equal access to environmental information and participation in decision-making processes—procedural justice—and a healthy environment for all social groups, representing substantive justice [41,42].

However, it is evident that environmental issues are not caused uniformly by all individuals and have varying impacts on different groups, leading to various challenges, including those related to gender inequality [43]. Women, in particular, face distinct and profound challenges due to climate change and environmental issues, which disproportionately affect them in several ways [44]. For instance, women are more affected by exposure to air pollution than men, primarily due to their greater involvement in domestic activities such as cooking or using cleaning products in most societies [45]. Women also constitute 80% of those displaced by climate change, facing increased risks of gender-based violence when uprooted [44]. The underrepresentation of women in environmental decision-making and key critical sectors for sustainable transitions also restricts their ability to influence policies that directly impact their lives [46]. Furthermore, economic strains from environmental changes not only lead to many girls being withdrawn from school to assist with domestic tasks but also result in women, who constitute a large portion of the agricultural workforce, having restricted land rights and representing less than 15% of landholders, often barring them from important resource management decisions [44].

Considering the abovementioned points, and despite the lack of extensive literature on this field, some authors dedicate their investigation to the relationship between air pollution and gender dynamics. For example, Kan et al. [47] examine the modifying effect of season, sex, age, and education on the relationship between outdoor air pollutants and daily mortality in Shanghai from 2001 to 2004. Their findings reveal that the percentage increase associated with higher air pollution levels varied between sexes. The impact of particulate matter $\leq 10 \mu\text{m}$ (PM₁₀) and ozone (O₃) on females was roughly double that on males, while the effect estimates of Sulphur Dioxide (SO₂) and Nitrogen Dioxide (NO₂) on overall mortality were marginally higher for females compared to males. Franklin et al. [48] studied the relationship between particulate matter $\leq 2.5 \mu\text{m}$ (PM_{2.5}) and all-cause and specific-cause mortality in the United States. These authors conclude that women are more susceptible to the effects of PM_{2.5} than men, specifically concerning cardiovascular mortality. Moreover, Huang et al. [49] analyze the exposure to PM_{2.5} in groups with different socio-demographic characteristics and inequalities in China. In this case, the

results show that age, education, occupation, and Gross Domestic Product (GDP) per capita affect these groups differently, but women and men had the same exposure to PM_{2.5}.

Identifying the effects of air pollution on different genders is crucial, especially concerning the role of women in governance and their capacity to mitigate environmental damage. Women, who are disproportionately affected, offer valuable insights into policymaking when they hold leadership positions. These perspectives are instrumental in shaping policies that address specific vulnerabilities and promote sustainable environmental practices. The subsequent section will explore how environmental policies can impact gender disparities.

2.2. Gendered Impacts of Environmental Policies

Some authors in the literature have highlighted how environmental policy can affect gender in different ways through their studies [50–54]. Indeed, Ling and Liu [54] investigate the role of women in overall environmental protection in China. These authors highlight that men still have a robust position in society, capable of blocking the expression and participation of women in environmental protection. As a result, environmental policies often adopt a gender-neutral stance, overlooking the differing impacts of environmental issues on women and men and neglecting the protection of women's interests.

Hemmati and Röhr [50] examine gender participation in climate change negotiations. They argue that tools and measures developed to combat climate change have the potential to exacerbate disparities, as they often fail to consider gender aspects. Additionally, Skinner [51] studied the linkage between gender and climate change, and this investigator states that policies in response to climate change focus on improving economic performance and seem to devalue gender disparities. Magnúsdóttir and Kronsell [52] explore the relationship between gender representation and climate policy development in Scandinavia. From their study, the authors conclude that the importance of gender is not considered in climate-making measures and that policymakers are mostly not cognizant of gender disparities on climate change issues.

From another perspective, Huang et al. [53] focus on comparing acceptable levels of individual exposure, perception, and PM_{2.5} with air pollution policy goals in three major cities in China. These authors' empirical outcomes indicate that the average daily PM_{2.5} exposure is significantly associated with gender, with women being the most affected gender. They also suggest that women and individuals exposed to intense haze pollution probably have lower trust in the government and seem to avoid outdoor activities.

This section briefly reviews the literature and emphasizes that environmental policies contribute to an increase in worldwide gender inequalities. Recognizing this is crucial for understanding the significance of women's leadership in fostering more inclusive and effective strategies for tackling environmental damage, given that they experience the consequences of environmental degradation differently and more pronouncedly than men due to societal roles, economic status, and health vulnerabilities. Subsequently, to understand the importance of environmental factors in political participation, we will highlight investigations that concentrate their attention on this relationship.

2.3. Environmental Impact on Political Participation

In recent decades, there has been an increase in environmental awareness among both the public and governments [55]. This rise can be attributed to the growing visibility of climate movements and media coverage [56]. Additionally, understanding the factors that drive public support for environmental initiatives is crucial for identifying the mechanisms to transition society toward a greener economy and a more sustainable future [56].

Indeed, air pollution can affect political participation in multiple ways [57]. Considering that air pollution poses a considerable risk to public health [58], prolonged exposure to it has been linked to reduced working days and lower worker output [59]. Consequently, decreased productivity leaves individuals less time for political activities [60], affecting political participation. Moreover, increased awareness of pollution levels can alter percep-

tions of local air quality, leading to high anxiety levels and more cautious behavior and reducing willingness to engage in community and civic activities [57]. Contrariwise, those adversely affected by ineffective policies may also become more inclined to participate due to a heightened personal commitment to addressing these issues. In this way, as a direct concern, air pollution can motivate individuals to engage in political action [57].

Considering the previous facts, some investigators dedicate their studies to the relationship between environmental issues and political participation (e.g., Hunnicutt and Henderson [57]; Hart and Feldman [61]; Yao et al. [62]). Hart and Feldman [61] evaluate the impact of both air pollution and climate change caused by power plant emissions on perceptions of the benefits and costs of emission-reduction policies and the intentions to engage in political action supporting these policies using an Ordinary Least Squares (OLS) methodology. Their findings highlight that individuals are more inclined to act against issues that have a direct and visible impact on them, such as smoke, compared to problems that seem temporally and spatially distant, like climate change. Hunnicutt and Henderson [57] investigate the linkages between policy failures, air pollution, and collective political participation in the United States. These authors conclude that air pollution (PM_{2.5}) can represent a barrier to political participation more than a stimulant. From another point of view, Yao et al. [62] explore the causal effect of PM_{2.5} concentrations on trust in local government, estimating a Two-Stage Least Squares (2SLS) model. The outcomes of this investigation state that the increase of PM_{2.5} negatively affects the trust in local government in China.

Moreover, this study reveals that individuals close to heavily polluting companies experience a more significant impact of PM_{2.5} concentration levels, suffering reduced life satisfaction, heightened environmental concerns, deteriorating health, and a lower opinion of local government performance. In contrast, from a business perspective, Khatib and Al Amosh [63] investigate the link between corporate governance and the environmental performance of companies, affirming that governance within enterprises also affects environmental concerns. Based on their findings, it is possible to conclude that companies with robust corporate governance are better positioned for carbon management. This can be attributed to these entities' effective oversight and control systems, enabling them to proactively adopt measures to reduce emissions, such as investing in renewable sources or developing policies to enhance energy efficiency.

Furthermore, political engagement in environmental issues is not equal by gender. Environmental factors disproportionately affect women due to inherent biological traits, such as their reproductive systems and physical attributes, and distinct social roles and behaviors, heightening their vulnerability to indoor pollution and challenges in accessing clean water and sanitation, particularly in rural areas [44]. Women also tend to adopt more environmentally friendly practices in their daily routines, such as using public transportation, recycling, or buying eco-friendly products, significantly contributing to a greener economy [46,64]. Furthermore, women in leadership roles are more inclined than men to support environmental initiatives and demonstrate greater caution toward environmental issues [64,65]. However, the infrastructure sector, encompassing energy, digital, and water services, exhibits a significant gender gap in employment and a scarcity of female leadership [64,66]. Addressing the underrepresentation of women in senior management positions is urgent, given their strong environmental commitment and critical role in supporting communities, leading conservation efforts, and enhancing business resilience [64]. This is crucial not only for the well-being of present and future generations but also for advancing the 2030 Agenda and boosting overall productivity.

Bearing the previous statements in mind, Fredriksson and Wang [67] investigated the relationship between female politicians and the environment in the United States House of Representatives and concluded that women are stricter on environmental policies than men. The research of Ergas and York [68] confirms the previous result. These investigators empirically assess the relationship between women's political status and CO₂ emissions using Ordinary Least Squares (OLS), and the findings reveal that countries where women

hold high political status have lower per capita CO₂ emissions. Atchison and Down [69] explore the effects of women's political representation on environmental policy in OECD countries. Their findings reveal that women exhibit a higher level of environmental concern than men and that female officeholders translate these distinct preferences into action.

Furthermore, Ramstetter and Habersack [70] analyzed the differences in environmental attitudes and actions between male and female members of the European Parliament. Despite both genders showing comparable levels of environmental concern, women were notably more inclined to support environmental legislation than their male counterparts. Moreover, May et al. [71] conducted a study examining the perspectives of male and female members of the Association of Environmental and Resource Economists (AERE) on environmental issues and policies. These authors divide their analysis into four groups. The first and second groups assess gender differences in support of government intervention, with the first group focusing on resolving environmental problems and the second on promoting change through tax incentives. The findings reveal that women exhibit more support for intervention through government regulation than men. Responses from the third group indicate that women are more concerned about social and environmental impacts than men. Lastly, the findings from the fourth group suggest that women are more inclined to support actions that are capable of responding to environmental challenges. El Khoury et al. [55] studied the behavioral disparities in political participation between women and men in Switzerland. The results indicate a gender gap in various daily pro-environmental behaviors (which include reusing products, limiting energy consumption, consuming fewer products, forgoing air travel, changing diet, and purchasing second-hand products), with women performing more pro-environmental behaviors than men. Their findings also indicate that gender behavior varies among private and public spheres, suggesting that if women had greater opportunities to get involved in institutional politics, they could be more active in the public sphere than in the private one, and we could expect more far-reaching social changes. Following a more specific perspective, Salamon [72] explores how women's parliamentary participation influences renewable energy policies. From the findings, this author concludes that increasing women's parliamentary involvement will increase renewable energy consumption, although not immediately. Zhang et al. [73] also focus on a different view, studying the effects of female CEOs on corporate environmental policies. They state that companies led by female directors may exhibit a stronger commitment to sustainable environmental practices, as women often demonstrate a greater orientation toward communal values and stakeholder considerations than men. Moreover, these authors consider that the presence of fellow women in leadership or influential positions could further amplify these pro-environmental tendencies among female CEOs.

However, other authors found a neutral effect. Jensen [74], in a study of the Norwegian Parliament, observed that environmental risk perceptions were influenced more by the party affiliations of the politicians than by their gender. Similarly, Gullett and Reingold [75] found no notable gender differences in environmental policy preferences and priorities among legislators in Arizona and California. Furthermore, Sundström and McCright [76], in their examination of the Swedish Parliament, determined that political orientation largely explains the gender differences in environmental concern.

After the preceding statements, which highlight the effects of environmental issues on political engagement in general and across genders and affirm the significance of women's political participation in reducing environmental damage, we will now delve into the specific examination of the potential relationship between PM_{2.5} concentration levels and women's representation in political leadership.

2.4. Existing Studies on the Interplay of PM_{2.5} and Women's Representation

To our knowledge, no studies theoretically or empirically directly link PM_{2.5} air pollution with women's political participation. However, we can derive insights into this relationship from the study conducted by York and Bell [31]. This research examines the impact of the political status of women on life satisfaction across 123 countries, applying

an OLS methodology. The primary finding is that the political status of women contributes to an increase in the general life satisfaction of individuals in these nations. To further illustrate their findings, the authors conducted a detailed analysis of Norway and Greece, selected for their contrasting levels of life satisfaction and different degrees of women's participation in parliament. They found that Norway, with its second-highest level of average life satisfaction and a substantial percentage of women in parliament, markedly differs from Greece, which has one of the lowest life satisfaction levels and one of the smallest percentages of women parliamentarians among developed countries. Furthermore, environmental quality is significantly better in Norway than in Greece, with Greece's PM_{2.5} levels more than doubling those of Norway. These statements suggest a positive correlation between higher women's political participation, better life satisfaction, and lower PM_{2.5} pollution levels.

Given the scarcity of existing literature on this topic, the next section will detail the conceptual framework between PM_{2.5} and women's political representation.

2.5. Conceptual Framework

Air pollution comprises a complex blend of different chemical compounds, predominantly Sulphur Dioxide (SO₂), Nitrogen Dioxide (NO₂), Carbon Monoxide (CO), benzo(a)pyrenes, and particulate matter with diameters of 2.5 µm or less (PM_{2.5}) and 10 µm or less (PM₁₀) [77]. Particulate matter (PM) is currently regarded as the most significant indicator of the health effects of air pollution, and according to the World Health Organization (WHO), it was responsible for the premature deaths of seven million people [78,79]. This pollutant is classified based on its diameter, with PM₁₀ comprising particles 10 µm or smaller and PM_{2.5} comprising particles 2.5 µm or smaller [79]. PM_{2.5} is particularly hazardous as it can easily penetrate the human body, resulting in multiple diseases.

Women, especially those who are pregnant, are among the groups most vulnerable to the harmful effects of PM_{2.5} [73,79]. This vulnerability can be attributed to their biological aspects and social, economic, and household roles. For instance, women's reproductive health can be severely affected by PM_{2.5} exposure [80]. Moreover, in many societies, women are primarily responsible for managing households and domestic work, such as cooking with fossil fuels and using cleaning products, which significantly increase PM_{2.5} levels and pose serious health risks [45]. Despite these challenges, women generally show more concern for environmental issues than men and are more likely to take pro-environmental actions [81]. This tendency can be attributed to the socialization of girls and women toward empathy and caregiving, making them more likely than men to perceive environmental threats as harmful not only to themselves but also to different species, such as animals and plants, and the biosphere in genera [69]. Additionally, women are often raised to value altruism more than men, a trait closely associated with environmentalism [82].

Considering the previous statements, women's political participation can significantly and positively influence environmental quality. According to DiRienzo and Das [83], women are capable of fostering a pro-environmental agenda (known as the absolute effect), especially when included in influential positions overseeing resources [84]. This inclusion leads to policies that address their health needs and benefit the broader community. In other words, women, having perspectives and preferences different from men, can develop more inclusive policies that address the needs of those most affected by environmental challenges and even push forward advancements that improve economic development [85]. Moreover, increasing gender equality within the political system can help diminish health disparities by promoting higher levels of investment in essential infrastructure like cleaner air and water [84]. Figure 3 resumes the previously described theoretical framework.

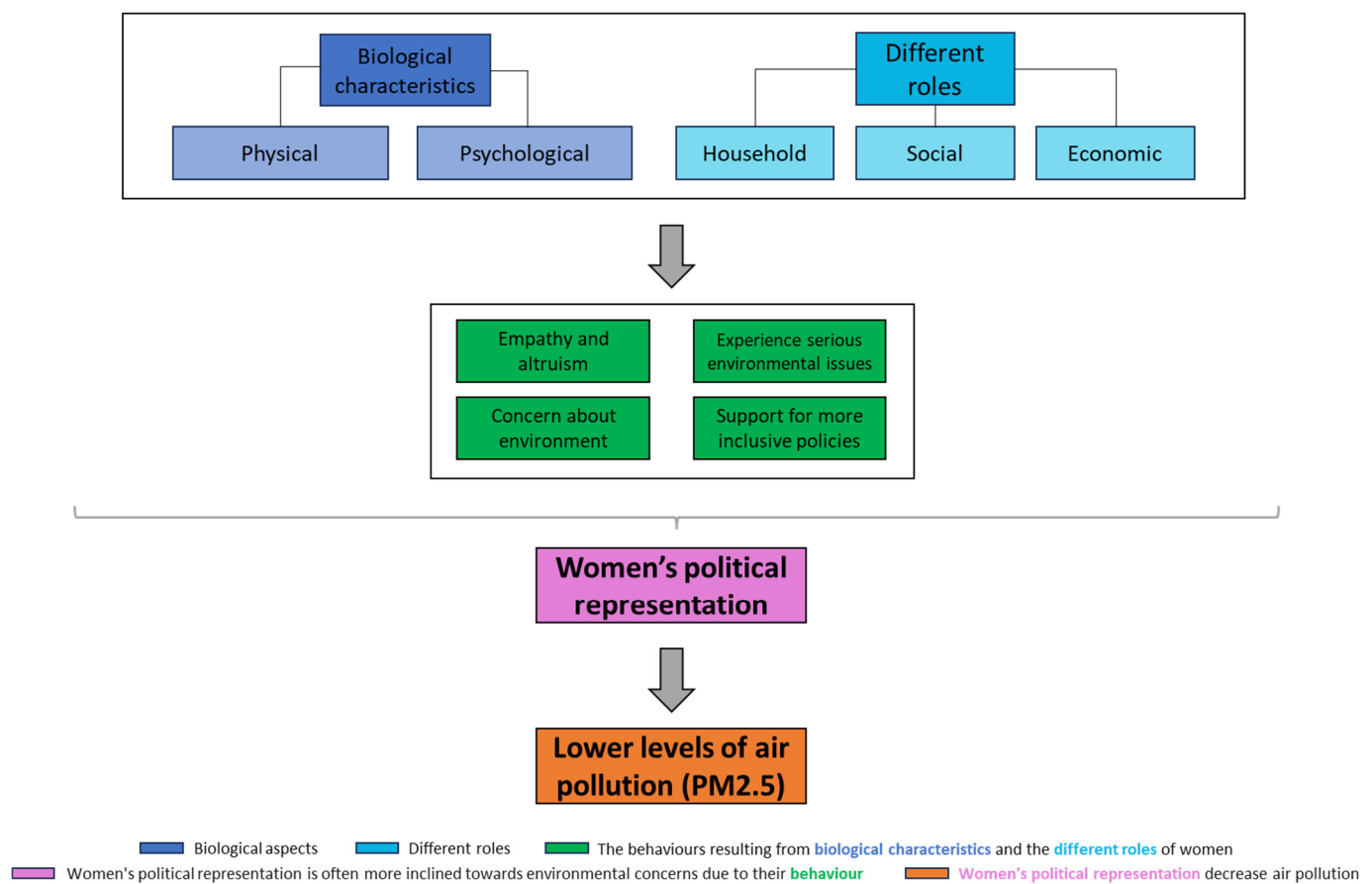


Figure 3. Conceptual model of the links between women's political representation and PM2.5 levels. The authors crafted this figure.

2.6. Research Gaps and Rationale for the Investigation

This review of the literature topics indicates that some questions need to be clarified. Firstly, the differential impact of PM2.5 air pollution on different genders is a critical area that has received limited attention. This gap in research is crucial given the potential unique health implications for different genders. Secondly, while there is recognition in the literature that environmental policies can exacerbate gender inequalities, a detailed understanding of how these policies differently affect women and men remains unclear. It is a significant oversight, considering the need for gender-responsive environmental policies.

Furthermore, most studies in previous fields focused on China indicate a geographical limitation in current research. Expanding this research to include diverse geographical contexts would provide a more comprehensive understanding of these issues globally. Finally, the most significant gap identified is the lack of direct investigation into the relationship between PM2.5 exposure and women's political leadership. Indeed, studies highlight the critical role of women's political participation in ensuring improved environmental performance, but not specifically on PM2.5 exposure.

Addressing these research gaps is indeed crucial. By exploring these areas, this investigation can enhance our understanding of the societal implications of environmental challenges, particularly gender dynamics. This research could provide valuable insights for policymakers and advocates working toward air pollution (specifically PM2.5), gender equality, and increased political participation.

3. Data and Method

3.1. Data

This investigation examines the connection between women's representation in political leadership and environmental pollution (PM2.5 emissions) across 27 EU countries, including Austria, Belgium, Bulgaria, Croatia, Cyprus, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, and Sweden.

Additionally, the study utilizes a time series spanning from 2013 to 2021. Several key factors justify the choice of this specific time frame:

- **Availability and Consistency of Data:** Data availability and consistency are crucial considerations in empirical research. The period from 2013 to 2021 offers a comprehensive and relatively consistent dataset for the 27 EU countries, allowing for robust analysis and meaningful comparisons across time and geographical regions.

By focusing on this time frame, this investigation can leverage a wide range of publicly available data sources, including official statistics, reports, and databases, which provide reliable and standardized information on various socio-economic and environmental indicators.

- **Relevance to Contemporary Issues:** The period from 2013 to 2021 corresponds to a significant time span characterized by numerous socio-political and environmental developments within the EU.

This period encompasses key policy initiatives, legislative changes, and societal trends related to gender equality, environmental sustainability, and public health, all of which have direct implications for our research focus on women's representation in political leadership and its impact on air quality (PM2.5 emissions).

- **Statistical Analysis and Interpretation:** Limiting the analysis to a defined time frame helps to ensure the coherence and interpretability of the statistical analysis. By examining data from a consistent period, this investigation can more accurately assess trends, patterns, and correlations, enhancing our findings' robustness and validity.

Moreover, focusing on a specific time frame facilitates the identification of causal relationships and temporal dynamics, allowing us to discern the short-term and long-term effects of women's representation in political leadership on PM2.5 emissions.

3.2. Variables and Sources

This investigation selected specific variables to analyze the relationship between various factors and the research objective. Table 1 outlines the chosen variables for this empirical analysis.

Table 1. Variables and sources.

Variable	Abbreviation	Description	Time Frequency	Unit of Measure	Source
Dependent variable					
PM2.5	PM2.5	Exposure to fine particulate matter (PM2.5)	Annual	Rate	OECD Data [37]
Renewable energy consumption	RENE	Renewable energy consumption (% of total final energy consumption)	Annual	Rate	World Bank Open Data [86]
Access to clean fuels for cooking	Ac_cfc	Access to clean fuels or technologies such as natural gas, electricity, and clean cookstoves	Annual	Rate	Our World in Data [87]

Table 1. Cont.

Variable	Abbreviation	Description	Time Frequency	Unit of Measure	Source
Proportion of women serving as ministers	Sm_w	The proportion of women serving as ministers (%)	Annual	Rate	European Institute for Gender Equality (EIGE) [38]
Proportion of women serving as members of parliament	Smp_w	The proportion of women serving as members of parliament (%)	Annual	Rate	European Institute for Gender Equality (EIGE) [38]
Proportion of women serving as members of regional assemblies	Smra_w	The proportion of women serving as members of regional assemblies (%)	Annual	Rate	European Institute for Gender Equality (EIGE) [38]
Proportion of women graduates of tertiary education	Gte_w	The proportion of women graduates of tertiary education (% 15+ population)	Annual	Rate	European Institute for Gender Equality (EIGE) [38]
Mean equivalized net income of women	Mei_w	Mean equivalized net income of women (PPS, 16+ population)	Annual	Euros (EUR)	European Institute for Gender Equality (EIGE) [38]

The dependent and independent variables have been meticulously chosen to assess their influence on the relationship between PM2.5 and women's representation in political leadership in the EU countries. Each variable has a scientific rationale based on previous research, as outlined below.

- Renewable energy consumption (RENE): Increased renewable energy consumption can lead to decreased reliance on fossil fuels, a significant source of air pollution, including PM2.5 emissions. Therefore, higher levels of renewable energy consumption might be associated with lower levels of PM2.5 pollution [88,89].
- Access to clean fuels for cooking (Ac_cfc): Clean fuels for cooking, such as natural gas and electricity, produce fewer indoor air pollutants than traditional solid fuels like wood or coal. Improved access to clean cooking fuels can reduce indoor air pollution, which may indirectly contribute to lower overall PM2.5 levels, especially in areas where indoor pollution contributes significantly to outdoor pollution [88,90].
- The proportion of women serving as members of ministries (Sm_w), parliament (Smp_w), regional assemblies (Smra_w), and graduates of tertiary education (Gte_w): Women's representation in government and higher education can lead to policies and initiatives aimed at improving air quality and public health, including measures to reduce PM2.5 emissions. Research has shown that gender-inclusive policies tend to focus more on environmental and health issues, which could indirectly affect PM2.5 levels through regulatory and legislative actions [31,47,51–54,57,61,62,76].
- Mean equivalized net income of women (Mei_w): Income levels, particularly for women, can influence access to resources and amenities that affect exposure to air pollution. Higher-income levels may enable individuals to live in less polluted areas or afford cleaner technologies, thus potentially reducing exposure to PM2.5 [49,91]

In summary, these variables are relevant because they capture aspects related to energy consumption patterns, access to clean technologies, gender representation in decision-making bodies, education levels, and socioeconomic status, all of which can influence policies, behaviors, and resources that impact air quality and, by extension, PM2.5 exposure levels.

3.3. Method

This section delves into the intricacies of the methodology, commencing with preliminary evaluations and culminating in applying both Pooled Ordinary Least Squares (OLS) and quantile regression (QREG) model regressions. Following the elucidation of the underlying theoretical framework, the subsequent phase systematically unveils the empirical research procedures to be executed with precision. The sequential progression of the empirical inquiry, outlined in Figure 4 below, serves as a strategic guide for translating theoretical underpinnings into actionable applications. These methodical steps are thoughtfully devised to bridge the gap between abstract concepts and the acquisition of tangible data, drawing concrete observations from real-world experiences.

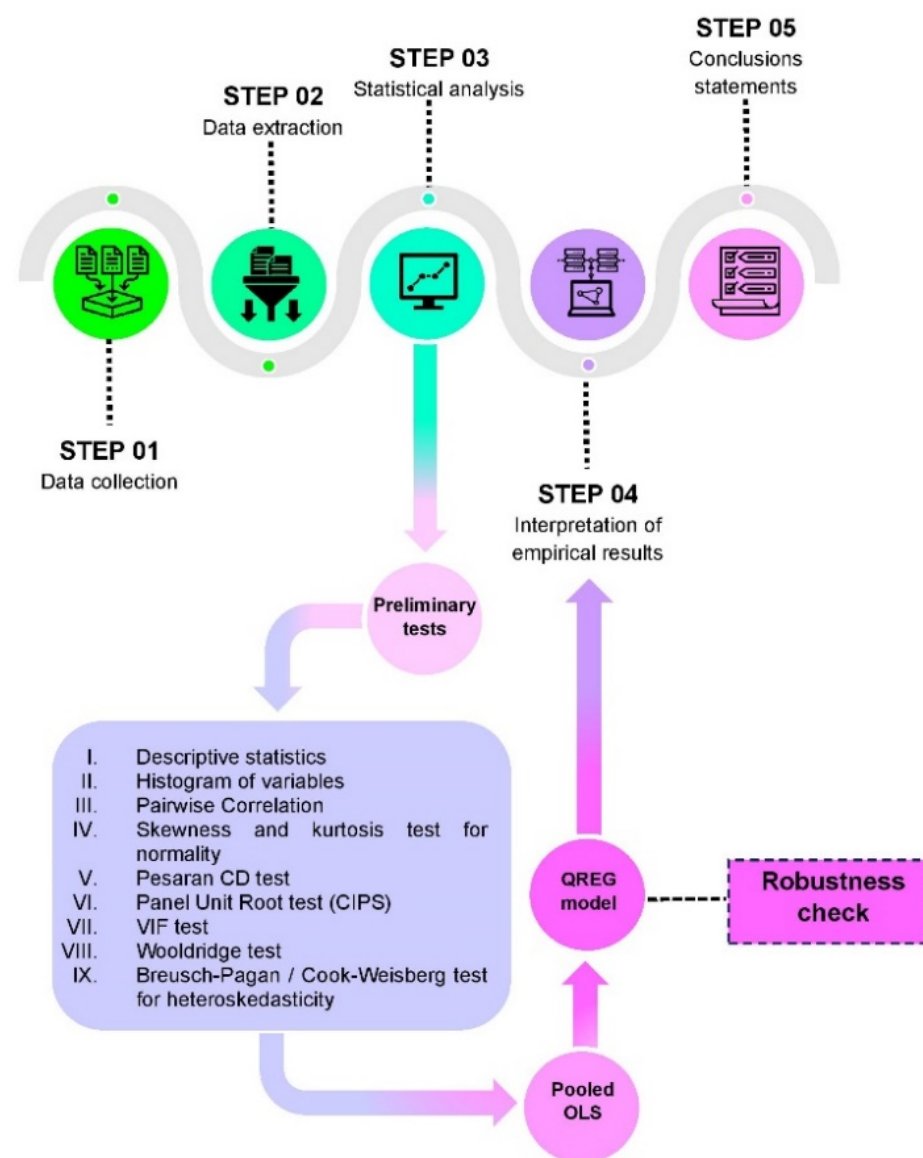


Figure 4. The steps of the empirical investigation are visually represented in the figure crafted by the authors.

Figure 4 visually outlines the sequential stages of the empirical investigation, illustrating the structured approach employed in this study. This well-designed framework bridges the gap between theory and practical implementation, ensuring a coherent and progressive investigative process. Each step is executed precisely to extract practical insights and substantial conclusions for academic scholarship and a practical understanding of the subject.

The rigorous adherence to these empirical investigation steps aims to validate theoretical hypotheses and shed light on complexities in real-world contexts, providing transparency for future research replication and extension [92,93].

3.3.1. Pooled Ordinary Least Squares (OLS) Model

The Pooled OLS model regression is a statistical methodology used to estimate the relationship between a dependent variable and one or more independent variables [94–96]. This model is a widely used statistical technique for estimating the relationship between a dependent variable (y) and one or more independent variables ($x_1, x_2, \dots, x_n$) in a pooled dataset. The general equation for the Pooled OLS model regression is expressed as follows:

$$y_{it} = \beta_0 + \beta_1 x_{1it} + \beta_2 x_{2it} + \dots + \beta_n x_{nit} + \varepsilon_{it}, \quad (1)$$

where, $x_1, \dots, x_{15}$ are the independent variables, $\beta_1, \dots, \beta_{15}$ are the regression coefficients representing the relationship between the independent variables and the dependent variable, and ε_{it} is the error term, representing the unexplained variation in the dependent variable.

Pooled OLS regression is chosen in this context to examine the impact of women's representation in political leadership in the European Union on PM2.5 emissions across 27 EU countries from 2013 to 2021 for several reasons. (i) Efficient Management of Extensive Datasets: Pooled OLS regression allows for the consolidation of data from multiple countries, thereby expanding the sample size and enhancing statistical power. This approach facilitates cross-country comparisons within the diverse contexts of the EU. (ii) Addressing Potential Confounding Factors: Pooled OLS regression enables a thorough exploration of the relationship between women's representation in political leadership and PM2.5 emissions while considering potential confounding factors. By controlling for these factors, researchers can better isolate the effects of gender representation on air pollution levels. (iii) Coefficient Estimates and Statistical Evidence: Pooled OLS regression provides coefficient estimates, which offer statistical evidence of the relationships between the examined variables. These estimates allow researchers to quantify the magnitude and significance of the effects of women's representation on PM2.5 emissions, informing policy decisions and interventions. In conclusion, Pooled OLS regression balances practicality, statistical robustness, and the ability to unveil meaningful insights into the complex interplay between women's representation in political leadership in the European Union and PM2.5 emissions while maintaining statistical validity. By employing this methodological approach, researchers can contribute to a better understanding of the role of gender dynamics in governance and their impact on environmental outcomes.

3.3.2. Quantile Regression (QREG) Model

This study utilizes QREG estimation to assess the robustness of Pooled OLS results. QREG extends traditional regression by estimating various quantiles of the response variable, providing deeper insights into how predictors influence different segments of the outcome's distribution. Introduced by Koenker and Bassett [97], this method differs from OLS by investigating changes in predictors across percentiles, making it robust to outliers, adaptable to diverse data patterns, and capable of revealing tail behavior. The basic linear quantile regression equation is represented as follows:

$$Q(y|x; \tau) = \beta_{0,\tau} + \beta_{1,\tau}x + \varepsilon \quad (2)$$

In this equation, $Q(y|x; \tau)$ represents the conditional quantile of the response variable y given the predictor variable x at quantile level τ . The coefficients $\beta_{0,\tau}$ and $\beta_{1,\tau}$ correspond to the intercept and slope of the regression line at the specified quantile τ , with epsilon representing the error term. By estimating these coefficients at various quantile levels, quantile regression offers a holistic view of how the relationship between variables evolves across distinct segments of the response distribution.

Therefore, the justification for utilizing the quantile regression (QREG) model in this study is based on several key considerations. (i) Robustness Check: QREG is employed as a robustness check to assess the reliability and stability of the results obtained from the Pooled Ordinary Least Squares (OLS) model. By comparing the findings from both models, this investigation can ascertain the consistency and robustness of the relationships between variables, particularly in the presence of outliers or non-normal data distributions. (ii) Accounting for Heterogeneity and Nonlinearity: Unlike OLS regression, which focuses on estimating the conditional mean of the response variable, QREG estimates various quantiles of the response variable's distribution. This approach allows us to capture heterogeneity and nonlinearity in the relationships between predictors and outcomes, providing a more comprehensive understanding of how these relationships vary across different segments of the data distribution. (iii) Handling Outliers and Extreme Values: QREG is particularly well-suited for handling outliers and extreme values in the data. By estimating quantiles at different levels (e.g., 25th, 50th, 75th, and 95th quantiles), this investigation can assess how the relationships between variables change across different parts of the data distribution, including extreme values and tail behavior. This ensures that this analysis is robust and not unduly influenced by outliers. (iv) Enhancing Model Reliability: By combining QREG with Pooled OLS, this investigation can conduct a comprehensive analysis of heterogeneity, outliers, and nonlinear relationships in the data. This approach enhances the reliability of this model by providing insights into the full range of data variations and ensuring a thorough evaluation of variable relationships. (v) Accommodating Data Variations: QREG's ability to estimate different quantiles accommodates variations in the data distribution, making it suitable for analyzing non-normal or outlier-rich datasets. This flexibility allows us to gain insights into extreme values and tail behavior, which may be critical for understanding the full spectrum of relationships between variables.

In summary, the utilization of the quantile regression (QREG) model in this study serves as a robustness check to enhance the reliability and validity of the findings of this investigation. By providing insights into heterogeneity, outliers, and nonlinear relationships, QREG complements the analysis conducted with Pooled OLS and ensures a comprehensive evaluation of variable relationships in this research context.

3.3.3. Preliminary Tests

Before applying the Pooled OLS and QREG estimators in the regressions, preliminary tests were crucial for understanding the characteristics of the variables within the economic model. The following tests were conducted.

- I. Descriptive Statistics: Computed metrics, including mean, standard deviation, minimum, maximum, and quartiles, offered a comprehensive summary of variable characteristics.
- II. Histogram of Variables: Visual depictions of variable distributions aided in identifying skewness, kurtosis, and potential outliers.
- III. Pairwise Correlation: Computed correlation coefficients revealed the strength and direction of linear relationships between variable pairs, highlighting interdependencies.
- IV. Skewness and Kurtosis Test for Normality: Tested whether each variable adhered to a normal distribution, assuming normality as the null hypothesis.
- V. Pesaran CD Test: Evaluated cross-sectional dependence within panel data, with the null hypothesis assuming its absence.
- VI. Pesaran [98] Panel Unit Root Test (CIPS): Assessed the stationarity of variables within panel data.
- VII. Variance Inflation Factor (VIF) Test: Examined multicollinearity among variables.
- VIII. Wooldridge Test for Autocorrelation in Panel Data: Scrutinized autocorrelation in the error term, with the null hypothesis assuming its absence.

- IX. Breusch–Pagan/Cook–Weisberg Test for Heteroskedasticity: Examined the presence of heteroskedasticity in the error term, assuming its absence as the null hypothesis.

These tests provided insights into variable characteristics and identified issues like non-normality, autocorrelation, or heteroskedasticity. In econometrics, these tests are recognized for enhancing model robustness and validity of Pooled OLS and QREG regressions [94–96].

Indeed, this empirical investigation used the econometric software Stata 17.0 (licence number 54389). The Stata commands used in this study included *sum*, *histogram*, *pwcorr*, *sktest*, *xtcd*, *vif*, *multiplot*, *xtserial*, *hettest*, *reg*, *reg robust*, and *qreg*, *quantile* (0.25 0.50 0.75 0.95). These commands were employed to conduct preliminary tests and model estimations. The following section will present the empirical results of this investigation.

4. Empirical Results

This section details data properties, preliminary variable testing, estimation outcomes, and testing for estimation specifications. Descriptive statistics and histograms for the variables used in empirical estimations are presented in Table 2 below.

Table 2. Descriptive statistics and histogram of variables.

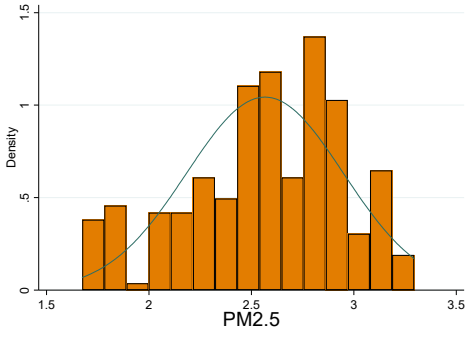
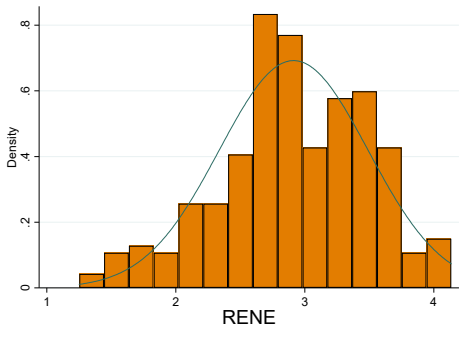
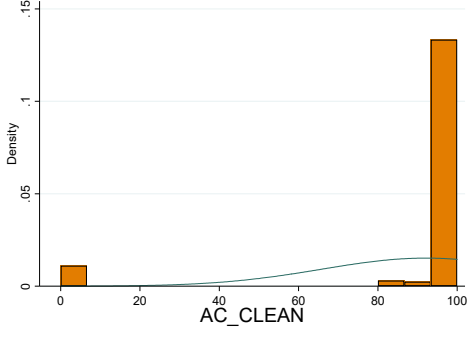
Variables	Obs	Mean	Std. Dev.	Min	Max	Histogram
Dependent variable						
PM2.5 (A)	243	2.5660	0.3823	1.6741	3.2946	
RENE (B)	243	2.9137	0.57633	1.2510	4.1363	
AC_CLEAN (C)	243	92.0927	26.2263	0.0000	100	

Table 2. Cont.

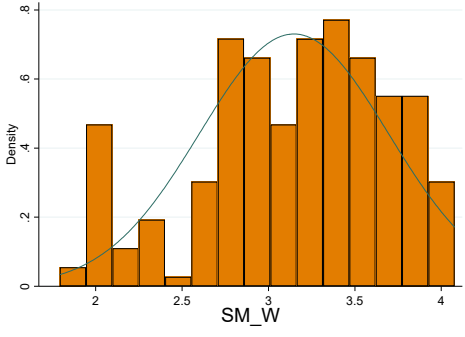
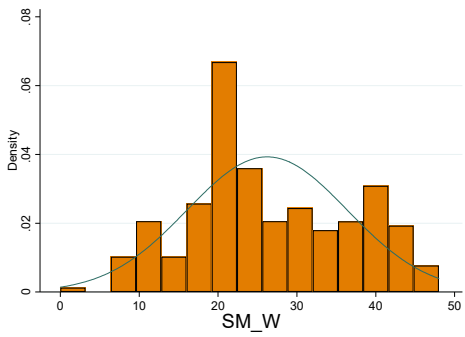
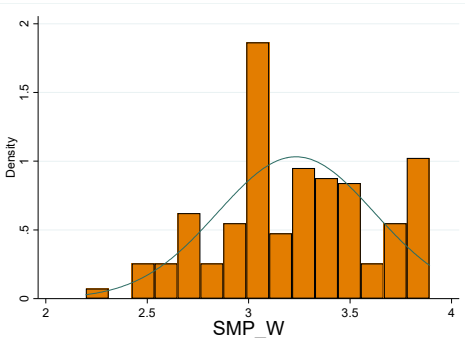
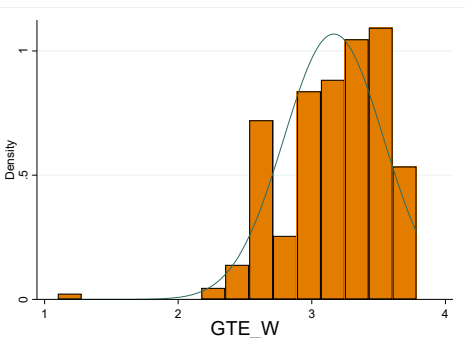
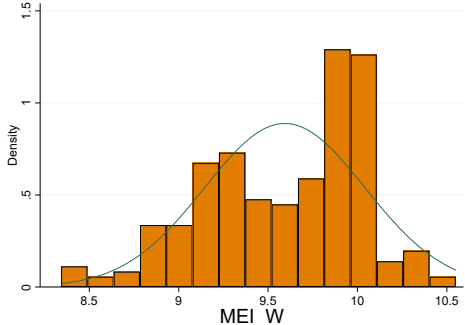
Variables	Obs	Mean	Std. Dev.	Min	Max	Histogram
Dependent variable						
SM_W (D)	238	3.1472	0.5461	1.7917	4.0775	
SMP_W (E)	243	26.2222	10.1541	0.0000	48	
SMRA_W (F)	242	3.2331	0.3864	2.1972	3.8918	
GTE_W (G)	240	3.1645	0.3734	1.0986	3.7841	

Table 2. Cont.

Variables	Obs	Mean	Std. Dev.	Min	Max	Histogram
Dependent variable						
MEI_W (H)	242	9.5935	0.4491	8.3418	10.5502	

Notes: The Stata commands “sum” and “histogram” were utilized for analysis.

Table 2 above presents descriptive statistics and histograms for various variables, providing crucial insights into their characteristics. Notably, the dependent variable PM2.5 displays a mean concentration of 2.5660 with low variability. Other variables, including RENE, AC_CLEAN, SM_W, SMP_W, SMRA_W, GTE_W, and MEI_W, exhibit diverse means and standard deviations, indicating distinct data patterns. These statistics collectively offer a comprehensive overview of the dataset, facilitating an understanding of central tendencies, variability, and the extent of disparity or consistency within each variable. Moreover, the histograms indicate a departure from a normal distribution, potentially impacting the statistical significance of the estimated parameters within the Pooled OLS model. Employing a QREG analysis can further investigate these deviations, enhancing the robustness of the results.

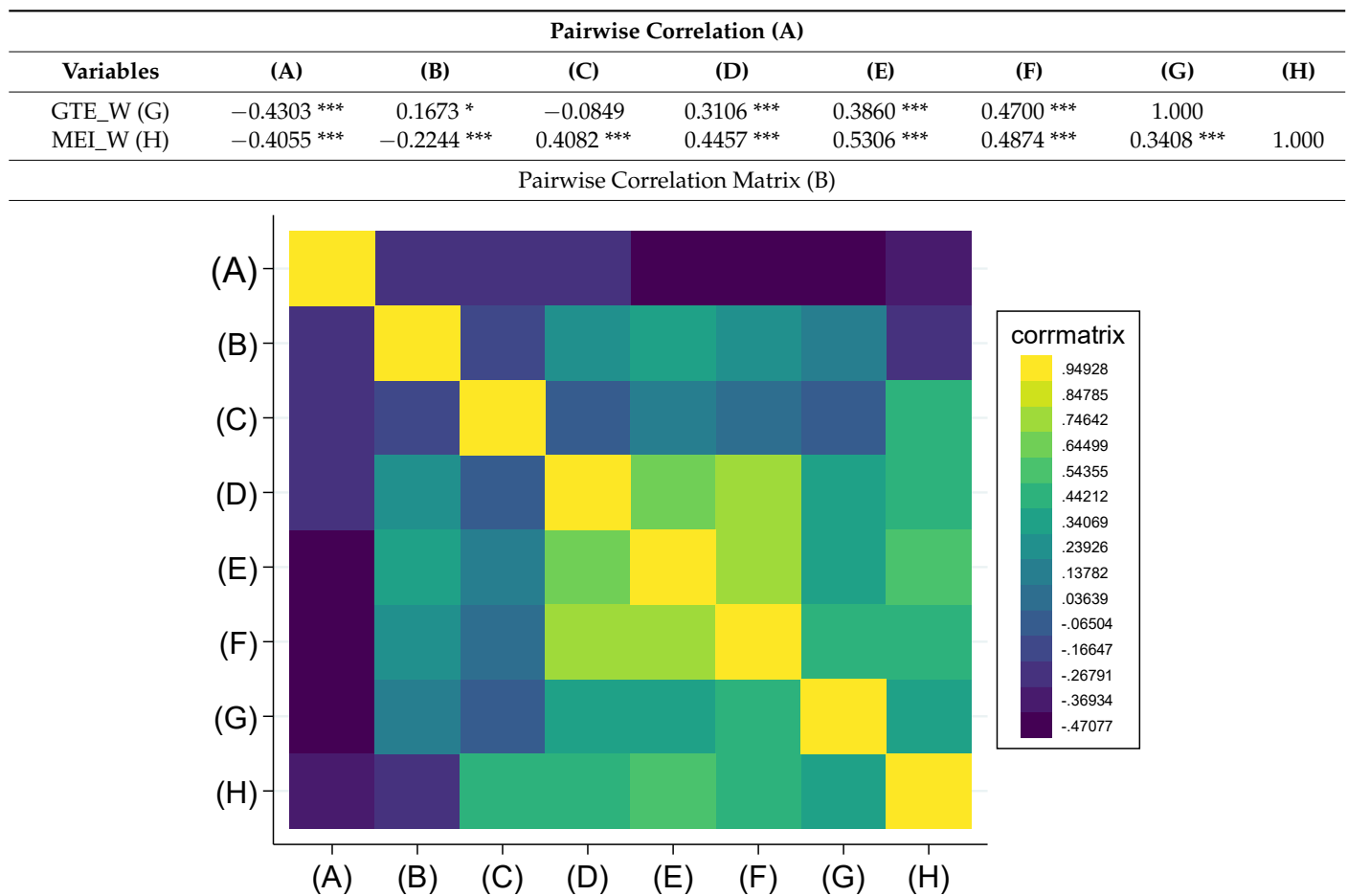
The subsequent phase involves conducting the pairwise correlation test, the results of which are presented in Table 3 below.

The pairwise correlation coefficients in Table 3 reveal associations between the variables. Notably, PM2.5 shows a negative correlation with RENE (−0.2866), AC_CLEAN (−0.2336), SM_W (−0.3105), SMP_W (−0.4880), SMRA_W (−0.5111), GTE_W (−0.4303), and MEI_W (−0.4055). The negative values suggest an inverse relationship, indicating that as PM2.5 concentrations increase, the corresponding variables tend to decrease. Additionally, some correlations between other variables are also observed. For example, there is a positive correlation between AC_CLEAN and MEI_W (0.4082). The significance levels denoted by asterisks indicate the strength of these correlations, with three asterisks representing a high significance level. These findings contribute to understanding the inter-relationships among the variables and provide insights into potential factors influencing PM2.5 concentrations.

Table 3. Pairwise correlation.

Variables	Pairwise Correlation (A)							
	(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)
PM2.5 (A)	1.000							
RENE (B)	−0.2866 ***	1.000						
AC_CLEAN (C)	−0.2336 ***	−0.2082 **	1.000					
SM_W (D)	−0.3105 ***	0.2690 ***	−0.1075 *	1.000				
SMP_W (E)	−0.4880 ***	0.3065 ***	0.1012	0.6894 ***	1.000			
SMRA_W (F)	−0.5111 ***	0.2879 ***	0.0439	0.7090 ***	0.7835 ***	1.000		

Table 3. Cont.



Notes: Concerning statistical significance, the symbols ***, **, and * correspond to significance levels of 1%, 5%, and 10%, respectively. The Stata command “*pwcorr*” was employed for analysis.

The following step entails performing the skewness and kurtosis test, with the corresponding results showcased in Table 4 below.

Table 4. Skewness and kurtosis test for normality.

Variables	Skewness/Kurtosis Tests for Normality					Obs
	Pr (Skewness)	Pr (Kurtosis)	Adj Chi2(2)	Statistic		
PM2.5 (A)	0.0027	0.1707	9.74	0.0077	*	243
RENE (B)	0.0185	0.8112	5.57	0.0617	*	243
AC_CLEAN (C)	0.0000	0.0000		0.0000	***	243
SM_W (D)	0.0013	0.0994	11.40	0.0033	**	238
SMP_W (E)	0.2005	0.0000	15.99	0.0003	***	243
SMRA_W (F)	0.5807	0.0095	6.73	0.0345	**	243
GTE_W (G)	0.0000	0.0000	37.85	0.0000	***	240
MEI_W (H)	0.0024	0.1910	9.79	0.0075	**	242

Notes: Regarding statistical significance, the symbols ***, **, and * correspond to significance levels of 1%, 5%, and 10%, respectively. The Stata command “*sktest*” was employed for analysis.

Table 4 above presents the results of skewness and kurtosis tests for normality on the variables. Notably, PM2.5 exhibits a skewness test *p*-value of 0.0027 and a kurtosis test *p*-value of 0.1707, suggesting a departure from normality. Similarly, other variables like RENE, AC_CLEAN, SM_W, SMP_W, SMRA_W, GTE_W, and MEI_W also display non-normal distributions based on their skewness and kurtosis tests, as indicated by asterisks

denoting significance levels. For instance, AC_CLEAN and GTE_W show extremely low p -values (0.0000) in skewness and kurtosis tests, implying a strong departure from normality. Moreover, the lower significance levels observed for PM2.5, Smra_w, MEI_W, and RENE in Table 4 are consistent with the complexities and non-normal distributions often observed in real-world data. These findings do not necessarily indicate a problem with the model but rather highlight the need to interpret the results in light of the variables' substantive relevance and the regression analysis's robustness.

The subsequent phase involves conducting the Pesaran CD test, the results of which are presented in Table 5 below.

Table 5. Pesaran CD test.

Variables	CD-Test	p -Value		Corr	Abs (Corr)	Obs
PM2.5 (A)	39.14	0.000	***	0.715	0.717	243
RENE (B)	35.38	0.000	***	0.628	0.717	243
AC_CLEAN (C)	N.a	N.a		N.a	N.a	243
SM_W (D)	7.03	0.000	***	0.128	0.437	238
SMP_W (E)	17.33	0.000	***	0.317	0.573	243
SMRA_W (F)	13.76	0.000	***	0.249	0.482	243
GTE_W (G)	43.72	0.000	***	0.787	0.868	240
MEI_W (H)	34.21	0.000	***	0.617	0.768	242

Notes: Concerning statistical significance, the symbol *** corresponds to a significance level of 1%. The Stata command “xtcd” was utilized for analysis. “N.a” indicates that the information is unavailable.

Table 5 above presents the results of the Pesaran CD test, evaluating cross-sectional dependence among the variables. The CD test statistics and p -values indicate significant cross-sectional dependence for all variables except AC_CLEAN, for which the test is not applicable (N.a). The correlation coefficients (corr) and absolute correlation coefficients (abs (corr)) further quantify the strength of the cross-sectional dependence. Notably, PM2.5, RENE, GTE_W, and MEI_W show high correlation coefficients ranging from 0.617 to 0.787, highlighting substantial cross-sectional dependence. These results suggest that the variables PM2.5, RENE, GTE_W, and MEI_W may be influenced by common factors, potentially impacting the assumption of independence in traditional statistical models.

The subsequent phase involves conducting the Panel Unit Root test (CIPS), the results of which are presented in Table 6 below.

Table 6. Pesaran [98] Panel Unit Root test (CIPS).

Pesaran (2007) Panel Unit Root Test (CIPS)							
Variables	Without Trend				With Trend		
	Lags		Zt-Bar			Zt-Bar	
PM2.5 (A)	0	−7.374	0.000	***	−5.788	0.000	***
	1	−2.379	0.000	***	12.957	1.000	
RENE (B)	0	−0.485	0.314		−1.267	0.103	
	1	−0.347	0.364		12.957	1.000	
AC_CLEAN (C)	0	16.097	1.000		12.957	1.000	
	1	16.176	1.000		12.957	1.000	
SM_W (D)	0		N.a			N.a	
	1		N.a			N.a	
SMP_W (E)	0		N.a			N.a	
	1		N.a			N.a	
SMRA_W (F)	0		N.a			N.a	
	1		N.a			N.a	

Table 6. Cont.

Variables	Pesaran (2007) Panel Unit Root Test (CIPS)					
	Without Trend			With Trend		
	Lags	Zt-Bar			Zt-Bar	
GTE_W (G)	0	−2.800	0.003	***	0.033	0.513
	1	−3.728	0.000	***	12.957	1.000
MEI_W (H)	0	0.859	0.805		1.555	0.940
	1	−4.043	0.000	***	12.957	1.000

Notes: Regarding statistical significance, the symbol *** represents significance levels of 1%. The Stata command “multipurt” was utilized for analysis. “N.a” signifies that the information is unavailable.

The results presented in Table 6, which depict the Panel Unit Root test (CIPS) outcomes, reveal interesting insights. Specifically, the independent variables PM2.5, GTE_W, and MEI_W exhibit borderline behavior between I(0) and I(1), hinting at a potential threshold effect in their stationarity. It is noteworthy that RENE and AC_CLEAN appear non-stationary; however, it is crucial to acknowledge that the short temporal dimension in longitudinal data might strongly contribute to this lack of stationarity, primarily attributed to short-run events. While this characteristic may not significantly impact Pooled OLS estimation, it could raise concerns during robustness analysis using the quantile regression model. Additionally, it is important to mention that the variables SM_W, SMP_W, and SMRA_W could not be computed in this test.

The subsequent phase involves conducting the VIF test, the results of which are presented in Table 7 below.

Table 7. VIF test.

Variables	VIF Test	Mean VIF
PM2.5 (A)	N.a	
RENE (B)	1.58	
AC_CLEAN (C)	1.52	
SM_W (D)	2.71	2.34
SMP_W (E)	3.27	
SMRA_W (F)	3.34	
GTE_W (G)	1.43	
MEI_W (H)	2.54	

Notes: “N.a” denotes “Not Applicable”. The Stata command utilized for this purpose was “vif”.

Table 7 above displays VIF test results for multicollinearity. Mean VIF values for variables, including RENE, AC_CLEAN, SM_W, SMP_W, SMRA_W, GTE_W, and MEI_W, range from 1.43 to 3.34, all below the commonly accepted threshold of 5. The absence of a VIF value for PM2.5 indicates its role as the dependent variable. These findings suggest that multicollinearity is not a significant concern among the independent variables, supporting the reliability of the regression analysis.

The subsequent phase involves conducting the Wooldridge and Breusch–Pagan/Cook–Weisberg tests, which are presented in Table 8 below.

Table 8. Wooldridge and Breusch–Pagan/Cook–Weisberg tests.

Wooldridge Test for Autocorrelation in Panel Data	Breusch–Pagan/Cook–Weisberg Test for Heteroskedasticity
F (1, 26) = 0.858	chi2(1) = 3.27 *

Notes: In the context of statistical significance, the symbol * corresponds to significance levels of 10%. The Stata commands “xtserial” and “hettest” were employed for analysis.

Table 8 above presents the outcomes of the Wooldridge autocorrelation test (H0: no first-order autocorrelation) and the Breusch–Pagan/Cook–Weisberg heteroskedasticity test

(H0: constant variance). No evidence of autocorrelation issues is observed. However, in light of the identified heteroskedasticity, employing the “robust” option during estimation is recommended to enhance the reliability of the regression model results.

Following a comprehensive set of initial assessments to identify potential concerns related to non-normality, unit roots, multicollinearity, autocorrelation, and heteroskedasticity that could impact subsequent model regressions, this study proceeds to implement the Pooled OLS regression. As previously highlighted, the Pooled OLS regression is the foundational model in this empirical analysis. Consequently, the outcomes of both the Pooled OLS and robust Pooled OLS approaches are presented in Table 9.

Table 9. Pooled OLS results.

Independent Variables	Dependent Variable (PM2.5 (A))						
	Pooled OLS				Robust Pooled OLS		
	Coef.	t	$p > t $	Significance	t	$p > t $	Significance
RENE (B)	−0.16053	−3.87	0.000	***	−4.24	0.000	***
AC_CLEAN (C)	−0.00255	−2.90	0.004	***	−3.77	0.000	***
SM_W (D)	0.11982	2.10	0.037	**	2.12	0.035	**
SMP_W (E)	−0.00717	−2.06	0.040	**	−1.99	0.047	**
SMRA_W (F)	−0.23223	−2.53	0.012	**	−2.78	0.006	***
GTE_W (G)	−0.22081	−3.65	0.000	***	−3.05	0.003	***
MEI_W (H)	−0.14987	−2.21	0.028	**	−2.44	0.015	**
Constant	5.9772	9.96	0.000	***	11.44	0.000	***
Number of obs	236				236		
F (7, 228)	24.96				34.44		
Prob > F	<0.001 ***				<0.001 ***		
R-squared	0.4338				0.4338		
Adj R-squared	0.4164				N.a		
Root MSE	0.29157				0.29157		

Notes: Regarding statistical significance, the symbols *** and ** correspond to 1% and 5% significance, respectively. The Stata commands “reg” and “reg robust” were employed for analysis. “N.a” indicates “Not applicable”.

The results presented in Table 9 underscore significant associations between the Pooled OLS and robust Pooled OLS estimators. Notably, certain independent variables—specifically, RENE, AC_CLEAN, SMP_W, SMRA_W, GTE_W, and MEI_W—demonstrate a negative correlation with reducing PM2.5 emissions in the EU. These variables exhibit statistically significant impacts, as reflected by their respective coefficients: −0.16053, −0.00255, −0.00717, −0.23223, −0.22081, and −0.14987. Conversely, another set of independent variables, such as SM_W, reveals a positive association with increased PM2.5 in the EU. This variable demonstrates a statistically significant impact, with a coefficient of 0.11982.

Following the Pooled OLS regression implementation, evaluating the stability of the obtained results in the initial model becomes imperative. The robustness check in this study utilizes QREG models, as outlined in the preceding section. The outcomes of the QREG model are subsequently detailed in Table 10 below. In this empirical investigation, the selected approach for assessing robustness involves the utilization of the 25th, 50th, 75th, and 95th quantiles.

The results from Table 10 highlight varying impacts of independent variables on the dependent variable PM2.5 across different quantiles. Specifically, the independent variable RENE exhibits a negative impact at the 25th, 50th, and 75th quantiles, suggesting a decrease in PM2.5 emissions. However, at the 95th quantile, RENE has a positive impact, indicating an increase in PM2.5 emissions. Similarly, AC_CLEAN negatively impacts the 25th and 50th quantiles dependent variable. SMRA_W has a consistently negative impact across the 25th, 50th, and 75th quantiles, while GTE_W shows a negative impact at the 25th and 50th quantiles, turning positive at the 95th quantile. Additionally, MEI_W has a negative impact on the dependent variable at the 75th and 95th quantiles. In contrast, independent variables

such as SM_W and SMP_W are statistically insignificant across all quantiles. Figure 5 below illustrates the outcomes derived from the QREG model at the 25th, 50th, 75th, and 95th quantiles.

Table 10. QREG model robustness check.

Independent Variables	Dependent Variable (PM2.5 (A))											
	Quantiles											
	0.25 Q			0.50 Q			0.75 Q			0.95 Q		
RENE (B)	−0.2067	0.004	***	−0.1926	0.000	***	−0.06335	0.270		0.2421	0.005	**
AC_CLEAN (C)	−0.0052	0.001	***	−0.0034	0.001	***	−0.0009	0.425		0.0021	0.247	
SM_W (D)	0.0333	0.733		0.1032	0.113		0.0782	0.323		0.0863	0.468	
SMP_W (E)	0.0044	0.458		−0.0049	0.211		−0.0050	0.296		−0.0099	0.170	
SMRA_W (F)	−0.3054	0.053	**	−0.2620	0.013	**	−0.2353	0.065	**	−0.0053	0.978	
GTE_W (G)	−0.4184	0.000	***	−0.2894	0.000	***	−0.0406	0.627		0.2215	0.079	*
MEI_W (H)	−0.0976	0.399		−0.0872	0.258		−0.2430	0.010	**	−0.3440	0.015	**
Constant	6.4585	0.000	***	5.8566	0.000	***	6.14468	0.000	***	4.7888	0.000	***

Notes: In the context of statistical significance, the symbols ***, **, and * correspond to significance levels of 1%, 5%, and 10%, respectively. The Stata command “qreg, quantile (0.25 0.5 0.75 0.95)” was employed for analysis.

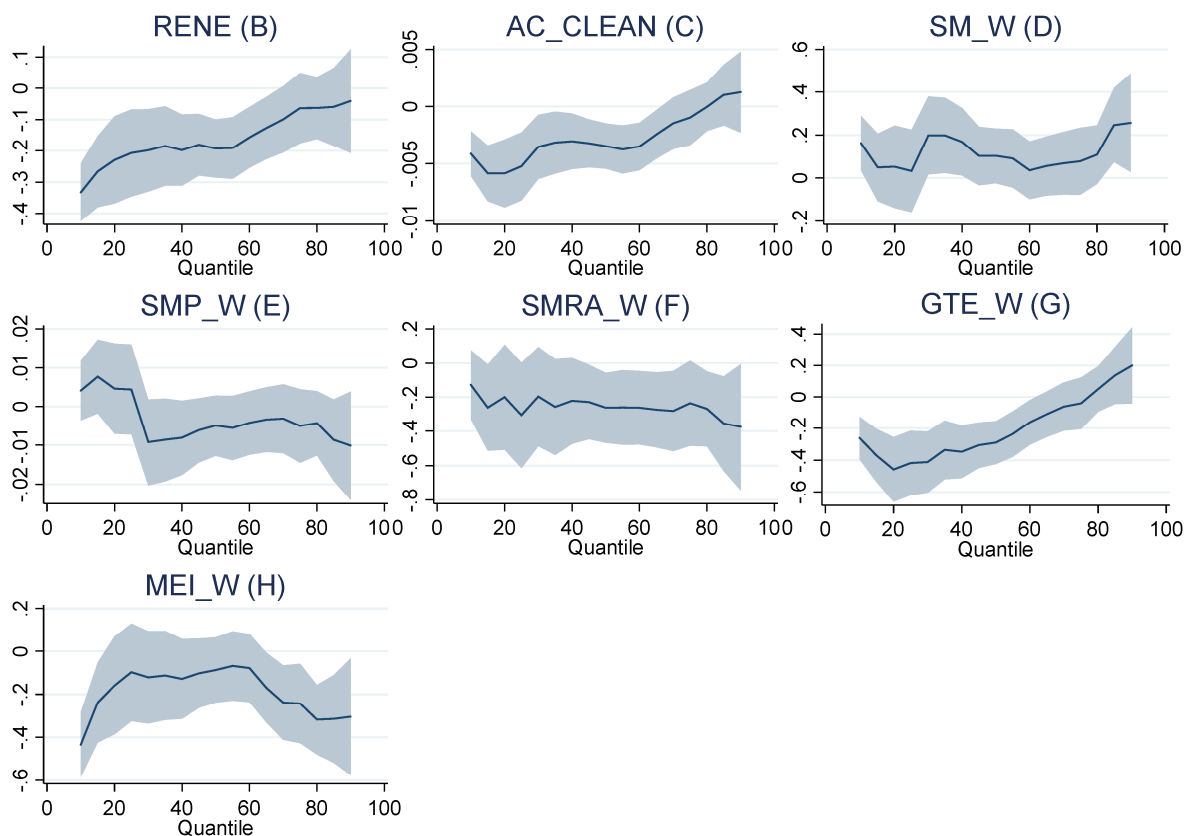


Figure 5. Graphical representation of QREG regression.

The results from Table 10 above align with those obtained in the OLS model, as detailed in Table 9. The identified associations between certain independent variables—namely, RENE, AC_CLEAN, SMP_W, SMRA_W, GTE_W, and MEI_W—demonstrate a consistent negative correlation with reducing PM2.5 emissions in the EU. These variables maintain statistically significant impacts, supported by their respective coefficients: −0.16053, −0.00255, −0.00717, −0.23223, −0.22081, and −0.14987. Conversely, another set of independent variables, such as SM_W, indicates a positive association with an increase in PM2.5 in the EU, supported by a statistically significant impact with a coefficient of 0.11982. This coherence

across models enhances the robustness of the observed associations and strengthens the reliability of the reported results. The following section will offer potential explanations for the empirical results presented in Table 9 above.

5. Discussion

This study highlights the significant impacts of women's representation in politics on pollution and PM2.5. Unlike other studies examining the impact of women's political participation roles on environmental policies with three separate variables (SM_W, SMP_W, and SMRA_W), which lead to more detailed results. Many academic studies agree that women have higher environmental awareness [99,100] and are more effective environmental activists than men [101,102]. However, in policymaking, there is no consensus in the literature that women are more active in the environment than men. However, many articles in the literature limit female representation in policymaking to the proportion of women in parliament [103], and the countries examined by some studies are very different from each other in sociological and economic terms.

The results showing a positive correlation between SM_W and PM2.5 in Table 9 are consistent with the results of other studies, such as Sundstrom and McCright [76] and Tremblay [104], which emphasize that the effects of female politicians on environmental policies do not differ from those of men. This relationship between SM_W and PM2.5 is compatible with Adams and Funk's [105] argument that in a male-dominated society, women in leadership positions behave like men, and the fact that women act in line with party policies in the decision-making process is one of the possible explanations for this result [76]. Additionally, female parliament ministers handle political issues typically associated with women, such as social security, children's rights, discrimination, and women's rights. Therefore, the sign of SM_W differing from SMP_W and SMRA_W, as seen below, reveals that the differentiation of women's political roles will also differentiate their effects on PM2.5.

Variables related to women's participation in politics show that women can play an important role in eliminating the negative effects of PM2.5 and environmental pollution and increasing the effectiveness of the fight for a clean environment. The fact that many studies do not differentiate the negative effects of the environment by gender conceals the fact that women may be more effective in this fight. The proportion of women serving as members of parliament and the proportion of women serving as members of regional assemblies, along with the negative correlation between PM2.5 and women's environmental policies, are similar to the results of Ergas and York [68] and Lv et al. [106]. SMP_W and SMRA_W variables are also associated with a high Environmental Performance Index [70,107,108], renewable energy use [72], and participation in international environmental agreements [65] and can indirectly have a reducing effect on PM2.5. It reveals that women are more stringent than men on environmental policies and may be more interventionist through government regulations than men [71]. In addition, the fact that women are more affected by PM2.5 than men [80] can be considered as a factor that will support them being more sensitive to environmental policies and public health issues.

Also, interestingly, the result shows that the negative correlation coefficients of women making politics on PM2.5 increase as we move down the representation hierarchy (SM_W, SMP_W, SMR_W).

Low-income countries and low-income groups are more exposed to PM2.5 and have health problems [109]. The econometric model results showing the negative correlation between women's income and PM2.5 are consistent with this situation. The increase in women's income can play a role in reducing PM2.5 by increasing environmental performance. This result is consistent with the findings of Lv et al. [106] and Domguia and Njoya [107]. This result can be explained in two different ways. First, higher income levels allow individuals to live in cleaner areas [108]. In addition, these results support the Environmental Kuznets Curve hypothesis, which states that developed countries and people are more sensitive about environmental policies, which is also valid for women.

The results show a negative correlation between education and PM2.5, in parallel with the results of studies in the literature [65,110,111]. The fact that young and less educated people are exposed to more of the negative effects of particulates is also consistent with these results [33]. These results show that education creates a social–environmental awareness and directs individuals to take responsibility for a sustainable future. Exposure to PM2.5 and air pollution can reduce worker productivity [59], may also reduce educational engagement behavior, and can negatively affect investments in education [112]. However, just as education increases environmental awareness, it can also cultivate the determination to prevent actions that contribute to air pollution.

The correlation between renewable energy consumption and PM2.5 is in the opposite direction, as expected and in line with the literature [18,113–115]. Increasing renewable energy consumption, such as wind and solar, reduces fossil fuel consumption and positively affects air quality, reducing PM2.5. Similarly, an increase in AC_CLEAN can negatively affect PM2.5. These results are supported by many studies stating that using clean energy, such as biofuel and hydroelectric, reduces indoor air pollution [116,117]. Clean cookstoves and access to natural gas reduce PM2.5, thus preventing household exposure to harmful particles [118]. However, in most European countries, kitchens are already designed to reduce PM2.5, which can be considered as the reason for the small coefficient of AC_CLEAN.

In addition to the negative effects of PM2.5 on human health, forest fires and dust storms caused by changing weather conditions due to climate change also negatively affect the quality of life. De Sario et al. [119] state that extreme weather events cause allergic diseases and respiratory difficulties. Climate change deteriorates air quality by increasing average temperature and greenhouse gas emissions. In addition, extreme rainfall, regional droughts, and hurricanes caused by global warming directly harm human health and also cause indirect damage by reducing air quality. Weilmhammer et al. [120] state that extreme heat and cold events increase mortality rates. Increasing average temperatures and droughts are associated with cardiovascular mortality rates. Extreme weather conditions not only affect physical health but also mental health, and some studies link climate change with depression and anxiety [121].

6. Conclusions

This research addresses a notable gap in existing research by establishing a direct link between PM2.5 air pollution and women's political participation. Despite a growing body of literature recognizing the gendered impacts on environmental issues and advocating actions for improvement, both theoretically and empirically, the scarcity of literature limits a comprehensive understanding of how gender differences can be leveraged to achieve better health outcomes. With the world facing significant environmental challenges, every contribution to mitigation efforts is crucial. This study illuminates the critical role of gender in governance and its impact on hazardous pollution emissions (PM2.5). It is a scientifically rigorous and exciting approach based on sound empirical principles.

To investigate the impact of gender in governance on dangerous pollution emissions, a study was conducted on 27 EU countries between 2013 and 2021 using econometric techniques such as Pooled OLS and quantile regression models. The combination of these methodologies was chosen due to the nature of the data and the relationships being researched. This study found that gender plays a distinct role in opposing pollution emissions and that the presence of women in parliaments and regional assemblies can reduce pollutant emissions. Additionally, this study discovered that enhancing women's education and increasing their average income can effectively mitigate dangerous pollutant emissions. However, further research is needed to fully understand the positive impact of women serving as ministers' members. This study also concluded that increased consumption of renewable energy and access to clean fuels for cooking could lead to decreased PM2.5 emissions. These findings highlight the importance of gender representation in governance and the promotion of clean energy sources to combat dangerous pollution emissions.

Policymakers must take an active role in creating social conditions that enable more women to participate in politics. One practical approach is to implement gender quotas, ensuring that women have access to decision-making positions where they can play a crucial role in shaping policies that limit environmental pollutants. Policymakers should combine efforts to achieve gender parity with initiatives to ensure clean air to maximize the positive impact of women's political representation. The underrepresentation of women in environmental decision-making and key sectors critical for sustainable transitions hampers their ability to influence policies and directly impact their lives. Therefore, removing barriers that prevent women from participating in vital resource management decisions is essential. Moreover, policymakers must promote greater awareness of the profound impact of the political sphere on the consequences of air pollution. By doing so, they contribute to a more informed and engaged public discourse on the intersection of gender, politics, and environmental issues. Finally, given the limited understanding of gender dynamics, society and policymakers, in particular, should be aware of the complexities of deliberately intervening in gender representation and be attentive to potential undesired effects it can have in other domains of society.

It is important to note that this research's scope and period might limit the generalization of the results. Therefore, cross-validation is necessary to ensure that the findings are not limited to the European Union and the analyzed timeframe. Gender-related phenomena require considerable time to evolve, and a relatively short period of nine years may present a somewhat incomplete picture of the phenomena being analyzed. More interdisciplinary research is required to understand the complexities of gender sensitivity to environmental degradation caused by pollutant emissions. A deeper exploration of the foundational aspects of this issue is necessary, and adopting complex approaches to uncover alternative combinations of the factors leading to similar outcomes becomes crucial. One such technique is fuzzy-set qualitative comparative analysis, which can be employed to pursue this approach. This would allow for a more nuanced understanding of the multifaceted nature of the topic, considering the intricate interplay of various factors contributing to the observed outcomes.

Future research can help us better understand how gender impacts democracy in politics and how it can improve government performance in combating harmful pollutants. Investigating how political affiliation and leadership roles influence women's involvement in pro-environmental activities is also necessary. Another area worth exploring is the role of gender in shaping lifestyles that actively contribute to improving environmental quality. Additionally, it is crucial to determine if a threshold for women's representation in political leadership triggers a noticeable and beneficial impact on reducing pollution. By studying these areas, future research can offer valuable insights into the complex dynamics between gender, politics, and environmental initiatives. This research can contribute to developing more effective and targeted policies for sustainable and eco-friendly practices.

This investigation is a comprehensive contribution to the United Nations Sustainable Development Goals (SDGs), covering various aspects of sustainable development. This study establishes a crucial connection between women's political participation and PM2.5 air pollution, addressing SDG 5. The research recognizes the complex relationship between gender dynamics in governance and environmental outcomes, actively promoting gender equality and empowering women and girls. Additionally, the findings align with SDG 3 by highlighting the direct impact of environmental pollution on public health and well-being. This study suggests gender-informed policies aimed at reducing pollution levels, which contribute to creating more sustainable and resilient urban environments, aligning with SDG 11. The investigation also supports SDG 7 by advocating for increased renewable energy consumption, which can help decrease PM2.5 emissions and ensure access to affordable, reliable, sustainable, and modern energy. Furthermore, this study emphasizes the importance of gender representation in decision-making processes, which aligns with SDG 16's goal of promoting inclusive, just, and strong institutions. Lastly, the research underscores the importance of partnerships for achieving common objectives related to

gender equality, environmental protection, and sustainable development, as highlighted in SDG 17.

This research comprehensively advances critical sustainable development elements and interconnects gender, politics, and environmental considerations.

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