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Assessing Impacts and Determinants of Urban Sustainability on Improving Air Quality Based on Entropy Weight Method in Coastal Cities, China*

Li, Meng-ying** · Jung, Ju-chul***

Abstract

With rapid socio-economic development and accelerated urbanization, air pollution has become one of the biggest concerns worldwide. Moreover, air quality affects people's quality of life and is addressed in Sustainable Development Goals (SDGs). It is important and meaningful to investigate the relationship between improved air quality and the level of urban sustainability to curb urban air pollution more effectively and provide a scientific basis for promoting sustainable urbanization. In this research, we employed the entropy weight method to measure the urban sustainable development level using the strength of urbanization efficiency indices, coordination degree indices, and sustainable urbanization indices from China's coastal cities panel data from 2014 to 2019. Next, we utilized the fixed effects model and dynamic panel model (System GMM) to estimate the impacts of sustainable urban development on improving air quality. According to the analysis, the main results were as follows: (1) Air pollution and urban sustainability indicated significant differences between 46 coastal cities in China; (2) Estimating the dynamic relationship between air pollution and urban sustainability, we found that air pollution has certain inertia: a 1% increase in the previous pollution concentration of PM_{10} and $PM_{2.5}$ will result in a 0.8% and 0.7% increase in the current pollution concentration of PM_{10} and $PM_{2.5}$. (3) Higher levels of urbanization effect, coordination degree, and sustainable urbanization contribute to decreasing the pollution concentration of PM_{10} and $PM_{2.5}$ in China.

Keywords Urban Sustainability Assessment, Entropy Weight, Air Quality, Panel Data, System GMM Estimation
주제어 도시 지속가능성 평가, 엔트로피 가중치, 대기질, 패널 데이터 모형, 시스템 GMM 추정

Ⅰ. Introduction

Sustainable development has been considered an important means to resolve urban problems (Malkina-Pykh, 2002). The correlation between the two concepts of urban development and sustainability was demonstrated in the United Nations' (UN) 2030 Agenda for Sustainable Development including Sustainable Development Goal (SDG) 11: "Sustainable Cities and Communities" (Maranghi et al., 2020). Discussions on sustainable development have mainly addressed environmental, economic, and social problems (Dempsey et al., 2011). Sustainable development in cities

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** PH.D. Student, Department of Urban Planning and Engineering, Pusan National University (First Author: limengying@pusan.ac.kr)
*** Professor, Department of Urban Planning and Engineering, Pusan National University (Corresponding Author: jcjung@pusan.ac.kr)
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consists of attempts to strike a balance among economic growth, protection of the ecological environment, and social development (Riley, 2001; Button, 2002; Repetti and Desthieux, 2006). In addition, the construction of livable, healthy, and safe cities have become the most important duty of each state, government, and organ today. In particular, China, as the largest developing nation worldwide, has undergone dramatic urbanization and industrialization since the Chinese economic reform of 1978. While China has accomplished a great success in economic growth and poverty reduction with the swift implementation of urbanization in the last 40 years, a severe environmental pollution problem such as air pollution has been caused in the development process. Against such a backdrop, the sustainable development of cities centering on the environment has even more importance and meaning. In 2014, the Chinese government attempted a new stage in the development of urbanization in order to resolve environmental and social problems caused by economic growth in the past several decades, announcing the National Urbanization Plan for the sustainable development of cities (Verdini and Zhang, 2020).

The world is becoming increasingly urbanized (Schell and Ulijaszek, 1999). At present, 50% or more of the world population lives in urban areas, and the ratio of population living in cities is expected to rise to 2/3 of the total population by 2030 (Matz et al., 2020; Zhang et al., 2020). The economy, society, and environment of cities, which are the centers of civic life, directly affect cities' ecological environments and the quality of citizens' lives (Harvey, 1989; Zhang et al., 2020; Alattar and Yousif, 2019; Huang et al., 2020). Today's development method, which focuses on the economy, has aggravated cities' environmental problems through continuous urbanization, population concentration, and industrialization. In particular, air pollution and climate change have emerged as globally important environmental problems (Lee et al., 2015). In 2016, the World Health Organization (WHO) estimated that the number of deaths due to air pollution would amount to 4.2 million per year. Out of air pollution, fine particulate matter ($PM_{2.5}$) pollution severely damaged human health (WHO, 2016a). Using satellite measurements and the atmospheric transport model, the WHO observed the atmospheric situation in over 100 nations and over 3,000 urban and rural areas around the globe in 2016. According to the results, it was revealed that 92% of the world population lived in areas polluted with coarse particulate matter (standard: the WHO's "The Air Quality Guidelines"[1)]) (WHO, 2016b; Zhang et al., 2020). In addition, it was announced that, as for atmospheric environment pollution generated in cities, the total amount of emitted pollutants exceeded the environmental carrying capacity and that this frequently gave rise to severe air pollution damages (Fleischmann and Feagin, 1987; Zhang et al., 2020). In particular, when research focusing on the health effects of deteriorated air quality is examined, it is apparent that air pollution increases respiratory disease and heart disease incidence rates in humans and that death rates due to air pollution increased continuously (Brunekreef and Holgate, 2002). There is also a report stating that not only 50% or more of the Chinese population is exposed to environments with air pollution but also 1/5 of deaths can be seen as due to air pollution (Zhang et al., 2020).

Many studies on the influencing factors of air quality have been conducted (Lee et al., 2015; Cruz et al., 2017; Molina-Gómez et al., 2020; Li and Jung, 2021). Previous research on the sustainable development of cities and the improvement of air quality distinguished the relationship of influence between sustainable development and the improvement of air quality between direct influence and indirect influence. As for direct influence, air quality is seen mainly as a level or an index influencing sustainable development. When air pollution is reduced and air quality is improved, the sustainable development of cities can be improved in a variety of ways (Zhao et al., 2020). When research on indirect influence is examined, the goal is mainly reducing air pollution and improving sustainable development. On the basis of factors causing air pollution such as urbanization, industrialization, population, socioeconomic growth, energy consumption, and traffic congestion, policies based on the perspective of sustainable development geared to the improvement of air quality are presented, and the validity of policies, too, is verified (Hosseinabad and Moraga, 2017). Strategies for sustainable development can play positive roles in the process of adjusting goals for socioeconomic development and a clean environment. In addition, mechanisms that analyze the influence of individual levels of sustainable urban development on the improvement of air quality hold important meanings for the establishment of policies for sustainable socioeconomic development and the resolution of the problem of air pollution.

Consequently, the purpose of this study is to verify the influencing and determining factors of urban sustainability on the improvement of urban air quality. On the basis of previous research, an urban sustainability assessment system (UCS) taking into consideration development level, coordination degree, and sustainability level, which are the three essential characteristics of sustainable development, was constructed. In addition, in order to verify whether or not sustainable development strategies were effective methods for mitigating urban air pollution, urban sustainability evaluations of 46 coastal Chinese cities were conducted through the use of the entropy weight calculation method, and the relationship between urban sustainability and air pollutants (PM_{10}, $PM_{2.5}$) was measured and analyzed through the use of a static panel model and a dynamic panel model estimated with the system generalized method of moments (GMM). Through this, the cities' sustainable development was evaluated, and plans for the improvement of the cities' atmospheric environments were presented.

Ⅱ. Literature Review

1. Review of Theories on Urban Sustainability and Air Pollution

1) Review of urban sustainability

"Sustainable development" is a widely used term. Discussions on sustainable development mainly address environmental, economic, and social problems (Dempsey et al., 2011). When in-depth meanings are examined, sustainable development promotes the overall development of society through economic development, efficient use of resources, and protection of the ecological environment. In other words, sustainable development and coordination development on the three levels of the environment, society, and economy are emphasized (Dias et al., 2014). Consequently, the sustainable development of the environment signifies that each person has a responsibility and a duty regarding environmental protection and improvement so that current environmental problems may not be transmitted to future generations (Tjallingii, 1995). Next, on the economic level, urban economies develop in the direction of efficiency, stability, and innovation (WHO, 1996). Finally, on the social level, sustainable development promotes information and cultural exchange (Yiftachel and Hedgcock, 1993). In addition, sustainable development can be realized when government organs, social public good organizations, and citizens all actively engage in discussions and participate in decision-making in order to resolve urban problems (Tjallingii, 1995).

The urban sustainability is a new concept presented after the construction global industrial cities. Supplementing the shortcomings and defects of the theory of the industrialization-based development of cities, this concept has provided a new theory and methodology regarding the healthy development of cities (Yang et al., 2017). Though similar, the concepts of "urban sustainability" and "sustainable urban development" differ in meaning. "Sustainability" stresses an ideal state maintained during the development process. In other words, it is a type of a series of constraints regarding development norms and socioeconomic development. Sustainability norms mainly stress that human society's socioeconomic development and the natural environment can coexist harmoniously and, at the same time, assume responsibility for future generations (Baumgärtner and Quaas, 2010). "Sustainable development" describes one development process. In other words, this is a process where sustainable development can be achieved in a situation where it has been initiated. "Sustainable development" emphasizes both the direction of development and the final developed state (Ravetz, 2000). Urban's environmental, economic, and social systems not only provide the bases and conditions for urban sustainability but also present the goals of urban development clearly (Wang and Guo, 2012). Consequently, it is apparent that sustainable urban development is a process of realizing urban sustainability and that urban sustainability is the ultimate goal of sustainable urban development (Maclaren, 1996). In addition, unlike sustainable urban development, urban sustainability has the advantage also of taking into consideration the effects of urban on the environments of the surrounding areas, regions, and the globe according to the spatial standard (Alberti, 1996). While providing diverse advantages such as economic growth, social progress, and improvement of urban residents' quality of life, at the same time, development based on dramatic urbanization, industrialization, and globalization has caused severe environmental pollution, especially prominent has been the problem of air pollution in cities and the regions where particulate matter is the main pollutant. Sustainable development has been increasingly stressed in order to respond to such problems so that urban sustainability likewise has received the attention of scholars and policy makers.

2) Review of urban air pollution

According to the report "Health and the Environment: Addressing the Health Impact of Air Pollution" presented at the WHO's 68th World Health Assembly (WHA) held in May 2015, over 7 million cases of premature death worldwide every year are related to air pollution. By 2015, cases of diseases due to air pollution are estimated to have outnumbered those of malaria, tuberculosis (TB), and acquired immunodeficiency syndrome (AIDS) combined (Wellenius et al., 2015). Air pollution thus not only has negative effects on human health and living environments but also lowers the quality of life.

Studies on air pollution have been actively conducted in diverse fields in recent years and all present the results that development based on urbanization and industrialization has clear, negative effects on air quality (Luo et al., 2017; Liu et al., 2017; Wang et al., 2017). Out of research on air pollution, there is a study that estimated the optimal city size for controlling air pollutants from the perspective of urban populations (Han et al., 2014). In addition, there is a study that explored the correlation between socioeconomic indices such as city areas, population density, and gross domestic product (GDP) and air pollution in terms of urban forms (Lin and Ouyang, 2014). Studies on air quality in urban areas mostly examined the effects of the socioeconomic growth of cities through development based on urbanization and industrialization on air quality. According to a study, out of them, urbanization caused the deterioration of urban air quality through complex mechanisms and can aggravate air pollutants emitted by factories and vehicles. According to the results of this study, urbanization can aggravate air pollutants emitted by factories and vehicles (Luo et al., 2017). On the contrary, there are studies claiming that development based on urbanization can improve air quality through the adjustment of economic structures such as marketization, globalization, and decentralization and institutional incentives such as local governments' and corporations' energy saving incentives (He et al., 2014; Zheng et al., 2017). In addition, when research on air pollution and development based on industrialization was examined, a correlation between industrialization-based development and air quality was clear. The fact that industrial exhaust gases can be reduced when innovations in the secondary industry and technology and the share of the tertiary industry rise helps to improve air quality (Zhang et al., 2020). Consequently, air pollution has become one of the types of environmental pollution gaining considerable attention worldwide, the improvement of the atmospheric environment is included in SDG 11.6, and the improvement of air quality not only is a priority in protecting public health but also can reduce negative effects of air pollution on the economy, human resources, and medical and public health expenses.

3) Urban sustainability and air pollution

Against the backdrop of sustainable development, air pollution is already worsening each day. In an outcome document titled "The Future We Want" and presented at the UN Conference on Sustainable Development (UNCSD) on July 27, 2012, national representatives promised to pursue sustainable policies in order to create a healthy atmospheric environment for sustainable cities and communities. In addition, the mitigation and improvement of air pollution were reported to have positive effects on human health, quality of life, and sustainable development (General Assembly, 2012).

Air quality has received considerable attention because it plays important roles in the process of achieving sustainable development. As for the relationship of influence between sustainable urban development and the improvement of air quality, previous research distinguished between direct and indirect effects.

As for direct effects, air quality is seen mainly as an index influencing sustainable development. Sustainable urban development can be improved in many ways if air pollution is reduced and air quality is improved. The results of a study argue that air pollution has the severest effects on human health (WHO, 2021). The WHO elucidated that long-term exposures to coarse particulate matter could result in severe effects on human health such as respiratory and cardiovascular diseases and lead to premature death in extreme cases (WHO, 2021). In addition, out of research on the spread of coronavirus disease 2019 (COVID-19) and air pollution, studies conducted during the first several months elucidated that the higher the concentration of air pollution was, the more easily people were infected with COVID-19. These studies claimed that airborne pollutants could help to spread severe acute respiratory syndrome (UN, International Day of Clean Air for Blue Skies). Moreover, there is a study arguing that air pollution is closely linked to climate change and that air pollutants are strong factors behind climate change (CCAC, Short-Lived Climate Pollutants). In addition, the results of a study that air pollution led to immense economic and productivity losses, crop yield reductions, and decreases in urban competitiveness in human society were presented. Global health damages due to air pollution were estimated to amount to 570 million dollars in 2016 alone. This was 4.8% of the world's GDP for 2016 (World Bank, 2016). The results of a study that air pollution affected social equity as well have been confirmed, too. In particular, air pollution affected medium- and low-income nations far more than it did advanced countries and severely affected the most vulnerable classes and local communities (OECD, Air Pollution Effects). Consequently, air pollution not only apparently has directs effects on "Good Health and Well-Being" (SDG 3), "Sustainable Cities and Communities" (SDG 11) and "Climate Action" (SDG 13) but also can indirectly influence other SDGs.

When studies on indirect effects were examined, under the goal mainly of reducing air pollution and improving sustainable development, they presented policies on the basis of factors causing air pollution such as urbanization, industrialization, demographic and socioeconomic growths, energy consumption increases, and traffic congestion from the perspective of sustainable development appropriate for air quality improvement and also verified the validity of the policies (Hosseinabad and Moraga, 2017). In particular, announced were the results of a study that research on the relations among energy-environment-sustainable development played key roles in raising sustainable investments in energy, promoting sustainable development, and improving air quality (Ahmad et al., 2020). In addition, from the perspective of energy consumption, a study sought to realize sustainable development and to improve the environment and air quality by reducing fossil fuel use and the development and use of green, renewable energy (Omer, 2007).

2. Review of Evaluations of Urban Sustainability

Sustainable development is a complex conceptual system encompassing society, economy, and environment, and evaluating urban sustainability is also a complex process (Zhang et al., 1999). Scholars at home and abroad universally use sustainable indicators to evaluate urban sustainability (Pelizer et al., 2004; Zhang, 2004; Wang et al., 2010; Fang et al., 2011; Nyuk et al., 2011; Yang et al., 2011; Cai and Chu, 2012; Liu et al., 2013; Sun et al., 2016a; Tran, 2016; Cui et al., 2019). Urban sustainability indices are a measure reflecting fundamental elements making possible the long-term and healthy development of urban economy, society, and environment and sustainable development (Fang et al., 2011). In addition, analysis methods using these indices are simple methods that not only facilitate an understanding of but also the quantification of the evaluation results, making it possible to grasp the situation of economic, social, and environmental development in a particular area (Kang and Lee, 2012; Ge et al., 2015). Consequently, developing urban sustainability evaluation indices has important meanings for sustainable urban development.

As for research on the development of urban sustainability index systems, mainly on the basis of the concept of sustainable development and through research on relations on multiple levels such as sustainable development and society, economy, environment, and resources, systematic evaluations of sustainable urban development were conducted.

(1) Sustainable development of societies and cities: Urban sustainable development pursues cities where mutual exchange occurs on the social level and information transmission and culture develop and that are symbolized by vitality, stability, and social fairness (Yiftachel and Hedgcock, 1993; Zhang et al., 1999). Based on this, domestic and overseas scholars' research on sustainability evaluations on the level of cities and societies mainly focused on clean air and potable water, living environment, educational opportunities, employment, poverty eradication, and medical facilities and services (Wang et al., 2010; Fang et al., 2011; Nyuk et al., 2011; Yang et al., 2011; Cai and Chu, 2012; Liu et al., 2013; Sun et al., 2016a; Tran, 2016).

(2) Sustainable development of the economy and cities: The WHO suggested that sustainable urban development must develop urban economies in the direction of greater

efficiency, stability, and innovativeness under the premise of minimal resource use (Zhang et al., 1999). Consequently, many scholars' research on evaluations of the sustainable development of urban economies focused mainly on improving the environmental efficiency of economic activities, reducing environmental costs due to economic activities, and developing hi-tech technological industries and the tertiary industry (Haughton and Hunter, 2004; Nijkamp and Perrels, 2014).

(3) Sustainable development of resources and cities: Sustainable urban development must rationally use resources in possession, purse green-friendly utilization methods, and stress actually high efficiency (Walter et al., 1992; Zhang et al., 1999). In addition, most research mainly established the protection of non-renewable resources, maximal use of renewable resources, and cyclical use of resources as the principles of sustainable urban development (Walter et al., 1994; Haughton, 1999; Zhang et al., 1999).

(4) Sustainable development of the environment and cities: The environment is the basis of human society's production and daily life (Xu, 1997). Economic and social development will be restricted by environmental conditions, and the environment's qualitative level will directly affect cities' sustainability and healthy development. A good urban environment not only raises people's quality of life and promote urban development but also forms an important part of urban sustainable development and has environmental effects on all aspects of urban sustainable development. Consequently, domestic and overseas scholars explored much in order to resolve the deterioration of the urban environment through research on urban sustainable development. When comprehensively examined, most studies presented environmental policies mainly on environmental problems arising per urban development stage(land abuse, air pollution, traffic congestion, etc.) that were relatively appropriate for environmental protection plans and urban planning (Cui et al., 2019). In addition, their principle was to select aspects of effects on pressure on the urban environment, environmental state, environmental responses, and urban environment as environmental evaluation indices (Xu et al., 2007).

3. Synthesis

Air pollution can affect not only the urban environment but also indirectly, social and economic development. A study on sustainable urban development and air pollution demonstrated that reducing air pollution aided urban sustainable development (Zhao et al., 2020). In addition, sustainable development was seen as an important means of resolving complex problems such as urban environment, society, and economy (Malkina-Pykh, 2002). Elucidating such relations, sustainable development strategies can play positive roles in the process of adjusting goals for socioeconomic development and a clean environment. In addition, mechanisms for analyzing effects on air quality improvement on individual levels of sustainable urban development have important meanings for the establishment of policies for sustainable socioeconomic development and the resolution of the problem of air pollution. In particular, in China, the target area of this study, it was pointed out that differences in urban air quality stemmed from imbalance in urban development (Fang and Liu, 2009). Consequently, this study established the following research question:

- Research question: Are sustainable development strategies an effective method for mitigating urban air pollution?

According to previous research, the birth and change of sustainable development are not abstract concepts but are realized through the three levels of the spatial dimension, element dimension, and temporal dimension of disparate measures of such theory and development patterns (Yang and Li, 2018). The spatial level mainly refers to concrete geographical units such as the world, nations, regions, cities, and even communities. The element level mainly concerns the three pillars of sustainable development, or sustainable economic development, sustainable social development, and sustainable environmental development. The temporal change level encompasses evaluations of the current state and development potential of sustainable development (Figure 1-a) (Yang and Li, 2018). In addition, when research on evaluation indices for sustainable urban development was synthesized, most studies focused on urban development levels and evaluated the current state of urban development with the corresponding social, economic, resource, and environmental indices (Yang et al., 2011; Cai and Chu, 2012; Liu et al., 2013; Sun et al., 2016a; Cui et al., 2019). Though some studies focused on cities' capacity for development, they

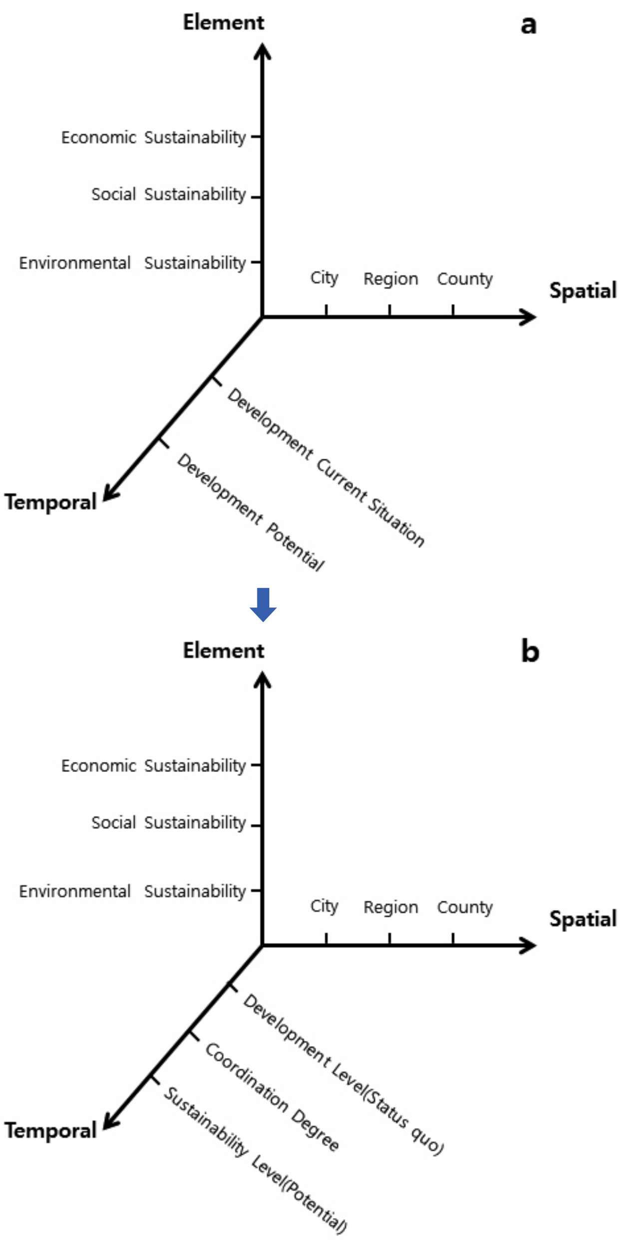

Figure 1. Three Dimensions of Sustainability Assessment

focused on policies regarding strategies to guarantee sustainable urban development (Hosseinabad and Moraga, 2017). Consequently, tools of urban sustainability evaluations remained at the stage of evaluations on the levels of urban development (i. e., results of development) and simple comparisons of total amounts, and insufficient was research on the capacity for sustainable development, coordination degrees among elements, and diversity of urban development. Announced in 2001, "Sustainability Science" defined the capacity for sustainability as the ability to provide support for maintaining local survival and fulfilling basic human needs systematically (Zhang et al., 2018). In summary, the three fundamental characteristics of sustainable development are the development level, coordination degree, and sustainability level. Therefore, based on the sustainability assessment of three dimensions (Figure 1-a) where the temporal dimension should contain the three characteristics of sustainable development. That is development current situation (Development level), the coordination between subsystem (Coordination degree) and the development potential (Sustainability level)(Figure 1-b) (Fang and Wang, 2011; Fang et al., 2015; Li and Jung, 2021).

Indicators research is a simple and easily quantified method, making it possible to grasp economic, social, and environmental development in a particular area. The results of indexation calculations of evaluation indicators make possible a convenient and prompt understanding of the sustainable development of the study areas. In addition, these results help policy makers to discover problems in urban development, to establish specific development goals, and to legislate sustainable development strategies (Ge et al., 2015). Consequently, this study took into consideration the three characteristics of the development level, coordination degree, and sustainability level of sustainable development on the basis of both previous research and the theory on the three dimension of sustainable development. Constructed was the UCS encompassing nine subcategories on the economic, social, and environmental dimension in addition to the three large categories of "Development level - Urbanization Efficiency Indices," "Coordination degree - Coordination Degree Indices," and "Sustainability level - Sustainable Urbanization Indices" (Figure 2).

The purpose of this study lay in verifying the influencing and determining factors of urban sustainability on the

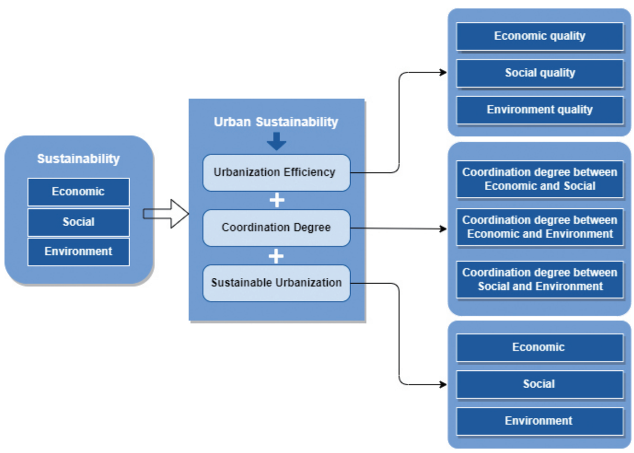

Figure 2. Urban Sustainability Assessment System (UCS)

improvement of urban air quality based on the theoretical examination and previous research mentioned above. In order to perceive problems with previous research and to verify whether or not sustainable development strategies were effective methods for mitigating urban air pollution, the following research hypotheses were constructed:

Research hypothesis 1: The higher the Urbanization Efficiency Indices (UEIs) are, the more air quality will be improved.

Research hypothesis 2: The higher the Coordination Degree Indices (CDIs) are, the more air quality will be improved.

Research hypothesis 3: The higher the Sustainable Urbanization Indices (SUIs) are, the more air quality will be improved.

Ⅲ. Research Methods

1. Target Areas and Scope of the Study

China has made great efforts to improve air pollution. Since the Chinese economic reform of 1978, both urbanization-based development rates population-based urbanization rates have increased. Though China has made great accomplishments in economic growth and poverty reduction with urbanization-based development over the past 40 years, that process has entailed severe destruction of the ecosystem as well. Against this backdrop, in 1993, China designated sustainable development as a national strategy in "Ten Strategies for Environment and Development" (Yang et al., 2017). In 2012, the Chinese Ministry of Ecology and Environment announced "Ambient Air Quality Standards," measuring $PM_{2.5}$ and O_3 and adjusting measurement concentration standards for PM_{10}, SO_2, and NO_2. In 2013, the State Council established "Air Pollution Prevention Plan" and presented the goal of lowering the air quality of Chinese cities on the prefectural level or above by 2017, by 10% in comparison with the figures for 2012. Announced in 2014, "National Urbanization Plan" attempts new stages in urbanization-based development and proposes sustainable urban development in order to resolve environmental and social problems caused by economic growth over the past several decades (Verdini and Zhang, 2020). In addition, since the third revision of "Air Pollution Prevention Plan" in 2015, the construction of ecological civilized cities has been stressed, and the improvement of air pollution and sustainable development have been emphasized as major goals. The Chinese government has adopted the control of environmental pollution as a state agenda and pursued a series of policies and programs begun to reduce environmental pollutant emissions (Zhao et al., 2018; Zhang et al., 2020).

As the spatial scope of this study, 46 cities on China's coast were selected (Figure 3). These 46 coastal cities measure 393,100 km^2 in area, taking up 4.04% of the nation's total area, and, as of 2019, their resident population was 16.37% of the total population, and their gross domestic product (GDP) took up 26.83% of that of the entire nation. Convenient in transportation and high in economic growth rates, these areas are relatively more developed than other Chinese cities. Because of preferential policy conditions and dramatic urbanization, these areas take up a very large share of China's economic development. These areas have seen the rise of environmental, resource, and social problems due to dra-

Figure 3. Study areas

matic economic development and, in particular, turned into ecologically vulnerable areas in the nation with the rise of severe environmental pollution problems including soil contamination, water quality decrease, air pollution, and ecological environment destruction as social problems (Li et al., 2020). With an increasingly prominent clash between economic development and environmental sustainability, these areas face great challenges in terms of urban sustainability.

2. Materials and Methods

1) Overview

This study's process of evaluating urban sustainability is as in the research flow in Figure 4. First, indicators needed for analysis were selected, a standardization process was implemented, weighted values were calculated using the entropy method, these weighted values were applied to standardized data, and urban sustainability was evaluated according to the aggregation method. The evaluation results were mapped using the geographic information system (GIS), and the results of evaluations of the urban sustainability of the study areas were analyzed comparatively. In addition, in order to grasp the effects of sustainable urban development on the improvement of air quality by using the evaluation results, panel data model analysis was conducted.

2) Selection and indexification of urban sustainability evaluation indices

The evaluation of urban sustainability is a long-term, systematic, and complex process encompassing diverse spatial dimensions (Yang et al., 2017). Scholars at home and abroad developed various methods and indices for the evaluation of sustainable urban development. These studies evaluated

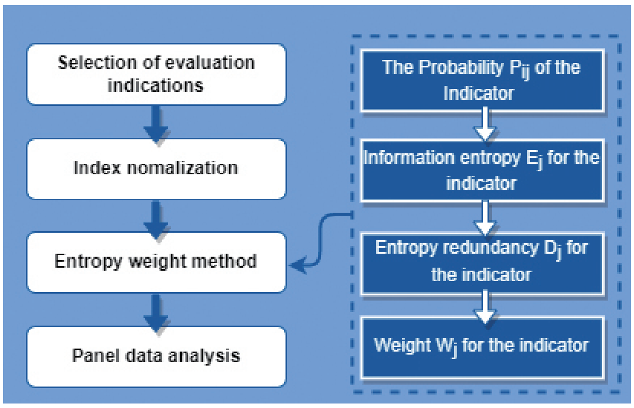

Figure 4. Study process

sustainable urban development mainly on diverse dimensions such as society, economy, environment, and resources.

Figure 2 shows the internal structure of the UCS. This study constructed a comprehensive index system in order to evaluate urban sustainability and subsystems. According to the results of the theory exploration and previous research, it was apparent that the development level, coordination degree, and sustainability level were the three fundamental characteristics of sustainable development. Based on this, (1) the UEIs indicate development level in this study. UEIs were measured through the three aspects of economic quality, social quality, and environmental quality. According to earlier research, the GDP per capita, secondary and tertiary industry ratios, energy consumption rate per GDP unit, and water use rate per GDP unit were used to explain economic quality (U1)(Zhang, 2004; Zhang and An, 2011; Huang and Huang, 2015; Sun et al., 2016a; Sun et al., 2016b; Cui et al., 2019). As for social quality (U2), the six indicators of citizens' Engel coefficient, urban residential area per capita, urban unemployment rate, number of physicians per 10,000 people, number of buses per 10,000 people, and road area per capita were used (Zhang, 2004; Fehr et al., 2004; Zhang and An, 2011; Sun et al., 2016a; Sun et al., 2016b; Cui et al., 2019). As for environmental quality (U3), the four indicators of the industrial wastewater discharge amount, factory exhaust gas emission amount, urban residential wastewater discharge amount, and ratio of an urban air quality index (AQI) of 2 or above were mainly used (Zhang, 2004; Pelizer et al., 2004; Sun et al., 2016a; Sun et al., 2016b; Song et al., 2016; Cui et al., 2019). (2) The CDIs indicate coordination degrees. They measured coordination degrees through the three categories of the coordination degrees between economic development and social development, between economic development and the environment, and between social development and the environment. In particular, under the goal of establishing local urban development strategies and plans according to research on evaluations of the sustainability of Chinese cities and on the basis of indicators that harmoniously measure the quality and quantity of urban development (Wang et al., 2010; Fang and Wang, 2011; Cui et al., 2019), it is possible to evaluate coordination within or among the internal systems and structures of the economy, society, and environment in the urban development process and also to assess equity in urban development with the nine basic indicators of the ratio of social welfare expenditure to the total financial expenditure, ratio of the public education expenditure to the GDP, residents' average wage, ratio of urban public structure construction investment costs to the GDP, ratio of environmental protection investment costs to the GDP, number of wastewater treatment facilities per 10,000 people, number of waste treatment facilities per 10,000 people, park green area per capita, and wastewater discharge amount per capita (Zhang, 2004; Pelizer et al., 2004; Yang and Shi, 2011). (3) The SUIs indicate sustainability levels and measure sustainability levels through the three aspects of the economy, society, and environment. Based on earlier research, the nine basic indicators of the economic growth rate, ratio of the increased tertiary industry to the GDP, ratio of the scientific and technological research expenditure for the development of hi-tech industries to the GDP, urban residents' subscription rate to basic medical insurance, social burden index, rate of turning industrial waste into resources, rate of rendering waste from daily life environment-friendly, and ratio of the financial expenditure for energy saving and environmental protection to the total financial expenditure were selected and used to explain the sustainability levels of cities on the economic, social, and environmental levels (Zhang, 2004; Pelizer et al., 2004; Yang and Shi, 2011). The specific indicators used in this study are as in Table 1.

The entropy method was applied first to thermodynamics, and, in 1948, Claude Shannon applied this thermodynamic term to information management (IM) science and used it in order to express the uncertainty of information (Jha and Singh, 2008; Shen et al., 2015). According to this principle, the greater the uncertainty of the result is, the higher is the probability of its distribution among them (Jha and Singh, 2008; Shen et al., 2015). This method is widely used in research fields such as economics, engineering, and finance. In addition, applications of this method can already be used in diverse fields such as the social sciences, urban planning, energy consumption, and landscape analysis (Zou et al., 2006; Shen et al., 2015). According to the results of existing research and practices, the entropy weight method, out of methods for determining the weighted values of evaluation indicators, can avoid the fallacy of researchers' subjective determination (Chen et al., 2013). It was perceived that this method could be utilized usefully in research on comprehensive evaluations of indicators. In addition, the method can not only take indicators' uncertainty into consideration but also explain in detail information related to indicators. Meanwhile, the value of entropy can be calculated to determine the degree of indicators' discreteness, and the greater the degree of indicators' discreteness is, the greater the effects of these indicators on the comprehensive evaluation system, or their share in the system, tend to be (Kim et al., 2012). Consequently, for urban sustainability evaluations, this study calculated evaluation indicators regarding urban sustainability through the entropy weight method by using 32 indicators encompassing the nine subcategories of the UEIs on the economic, social, and environmental levels, the CDIs among the economy, society, and environment, and the SUIs for the economy, society, and environment.

First, in order to correct differences in indicators units, data were standardized (Li et al., 2012). All index values x_{ij} were normalized as [0, 1].

$$\text{Positive data}: X_{ij} = \frac{x_{ij} - x_{ij}\min}{x_{ij}\max - x_{ij}\min} \tag{1}$$

$$\text{Negative data}: X_{ij} = \frac{x_{ij}\max - x_{ij}}{x_{ij}\max - x_{ij}\min} \tag{2}$$

x_{ij} : variable value

i : year

j : index

$x_{ij}\max$, $x_{ij}\min$: maximum value, minimum value

The process of calculating the weighted value for each major index was determined as follows:

(1) Indicator x_j is the probability P_{ij} within the year i :

$$P_{ij} = \frac{X_{ij}}{\sum_{i=1}^{n} X_{ij}} \tag{3}$$

(2) Entropy E_j of indicator x_j:

$$E_j = -\frac{1}{\ln n} \sum_{i=1}^{n} (P_{ij} \times \ln P_{ij}) \tag{4}$$

(3) Entropic redundancy D_j of indicator j :

$$D_j = 1 - E_j \tag{5}$$

(4) Weighted value W_j of index j :

$$W_j = \frac{D_j}{\sum_{j=1}^{m} D_j} \tag{6}$$

Table 1. Urban sustainability assessment indicators

Variable name		Explanation	Unit	
Urbanization Efficiency Indices (U)	Economic quality (U1)	X1: GDP per capita	yuan	+
		X2: Percentage of the secondary and tertiary industry	%	+
		X3: Energy consumption per unit of GDP	t/yuan	-
		X4: Water consumption per unit of GDP	m^3 /10^4 yuan	-
	Social quality (U2)	X5: Citizen Engel's Coefficient		-
		X6: Urban per capita living space	m^2	+
		X7: Urban unemployment rate	%	-
		X8: Number of college students per 10000 population	Pop	+
		X9: Number of doctors per 10000 population		
		X10: Number of buses per 10000 population	Num	+
		X11: Road areas per capita	m^2	+
	Environment quality (U3)	X12: Discharged of waste water per unit of GDP	t/10^4 yuan	-
		X13: Green covered area as % of Completed	%	+
		X14: Proportion of air quality equal to and better than level II	%	+
Coordination Degree Indices (C)	Coordination Degree Economic and Social (C1)	X15: Financial expenditure for a social safety net in general public expenditure rate	%	-
		X16: Financial expenditure for education as a percent of GDP	%	+
		X17: Real average wage		
	Coordination Degree Economic and Environment (C2)	X18: Financial expenditure for municipal infrastructure as a percent of GDP	%	+
		X19: Total investment in the treatment of environmental pollution as a percent of GDP	%	+
		X20: Sewage treatment plants per 10000 people		+
		X21: Garbage disposal plants per 10000 people		+
	Coordination Degree Social and Environment(C3)	X22: Park green areas per capita	m^2	+
		X23: Life waste harmless treatment rate	m^3	+
Sustainable Urbanization Indices (S)	Economy (S1)	X24: Sustained economic growth	%	+
		X25: The share of the added-value of the tertiary industry in GDP	%	+
		X26: Expenditure for science and technology as a percent of GDP	%	+
	Society (S2)	X27: Percentage of urban residents with basic medical insurance	%	+
		X28: Social burden coefficient	%	-
		X29: Average per capita income elasticity		+
	Environment (S3)	X30: Industrial waste material recycle rate	%	+
		X31: Treatment rate of industrial effluents	%	+
		X32: Financial expenditures on energy conservation and environmental protection in general public expenditure rate	%	+

Sources: China Statistical Yearbook, China Statistical Yearbook of Environment, China Energy Statistical Yearbook, China City Statistical Yearbook (2016-2020)

Here, n is the temporal scope (years) of this study, and m is the number of indicator. Finally, the comprehensive index S_i of each evaluation indicator is calculated:

$$S_i = \sum_{j=1}^{m} W_i \times X_{ij} \tag{7}$$

3) Establishment of variables and analytical model

To verify this study's hypotheses, PM_{10} and $PM_{2.5}$, which are major air pollutants, were selected as this study's dependent variables, and, as for data on the annual average PM_{10} and $PM_{2.5}$ pollution concentrations, the annual average PM_{10} and $PM_{2.5}$ pollution concentrations provided by the China Statistical Yearbook of Environment according to "New Atmospheric Environment Standards" of 2012 were used. Urban sustainability was established as the independent variable, and nine evaluation indices calculated through the entropy weight method were used: the UEIs on the economic, social, and environmental levels; the CDIs among the economy, society, and environment; and the SUIs for the economy, society, and environment (Table 2).

In order to grasp causal relations between the dependent variables and the independent variable, this study confirmed a third variable exerting influence between the dependent variables and the independent variable and, in order to remove its influence, selected control variables (Namkoong et al., 2017). Consequently, previous research on urban air quality mentioned above was analyzed, and the control variables of this study were selected on the basis of variables with high significance out of variables causing urban air pollution in previous studies. The finally selected control variables were population density, industrial areas, and number of private automobiles.

In addition, before analyzing panel data regression models, analysis of correlation among variables and analysis of variance (ANOVA) were conducted. The purpose of ANOVA is to estimate differences among groups, and homogeneity tests of variance can be conducted. This study used ANOVA to analyze differences between coarse particulate matter (PM_{10}) and fine particulate matter ($PM_{2.5}$) in the annual average concentrations per region and time. According to the ANOVA results, as in Table 3, the annual average coarse particulate matter (PM_{10}) and fine particulate matter ($PM_{2.5}$) concentrations exhibited significant differences per city and time.

Table 2. Variables

Variables	Explanation
Dependent variable (Y)	
Variables	Explanation
$PM_{2.5}$	The mean annual concentration of suspended particulate matter (ug/m^3)
PM_{10}	The mean annual concentration of suspended particulate matter (ug/m^3)
Independent variable (X)	
Urbanization Efficiency Indices (U)	
Variables	Explanation
U1	Urbanization Efficiency_Economic quality
U2	Urbanization Efficiency_Social quality
U3	Urbanization Efficiency_Environment quality
Coordination Degree Indices (C)	
Variables	Explanation
C1	Coordination Degree between Economic and Social
C2	Coordination Degree between Economic and Environment
C3	Coordination Degree between Social and Environment
Sustainable Urbanization Indices (S)	
Variables	Explanation
S1	Sustainable Urbanization_Economy
S2	Sustainable Urbanization_Society
S3	Sustainable Urbanization_Environment
Control variable (Z)	
Variables	Explanation
Density	Population density (Pop/km^2)
Commercial	Commercial area (km^2)
Industrial	Industrial area (km^2)
Private cars	Number of private cars (10000 units)

Sources: Yearbook of China, China Statistical Yearbook of Environment, China Energy Statistical Yearbook, The Almanac of China's Cities (2013-2020)

Before analyzing panel data regression models, the variance inflation factor (VIF) was used to conduct multicollinearity tests of individual panel data. The VIF is a coefficient of variance expansion, and the VIF value is the method most commonly used to test multicollinearity (Liu et al., 2017; Zhao et al., 2016; Zhou et al., 2018; Han et al., 2020). According to the VIF method, it is demonstrated that a model has no problem with multicollinearity when the VIF value of the root variable is smaller than 10 (Gujarati and Porter, 2009; Chatterjee and Hadi, 2006; Zhao et al., 2016; Zhou et al., 2018). Consequently, this study eliminated from models

Table 3. Results of test

Test	$PM_{2.5}$	PM_{10}
ANOVA test (time) F	15.80***	22.52***
ANOVA test (region) F	10.11***	6.71***
Wooldridge test for auocrrelation in panel data F	84.908**	73.321***
Modified wald test for groupwise heteroskedasticity χ^2	1124.46***	3935.56***
Frees' test of cross sectional independence	3.950 > 0.5676 (5% critical value)	2.968 > 0.5676 (5% critical value)
Hausman test χ^2	223.39***	268.09***

Note: Significant levels ~p<0.1* ~p<0.05** ~p<0.01***

variables with VIF values greater than 10. In addition, before panel data regression models were estimated, models' adherence to the hypotheses was verified, and, in particular, serial correlation and heteroscedasticity tests of panel data were conducted (Lee and Noh, 2013). In addition, this study verified the groups' heteroscedasticity and autocorrelation by using the revised Wald test and the revised Wooldridge test.

In general, panel regression models test the significance of the fixed effect and the random effect with respect to the individual effect and the time effect of panel models combining cross-section data and serial data for research purposes, and when both effects are significant, the characteristics of the data and appropriate models are established as the models for final analysis through the Hausman test (Lee et al., 2013).

Because the Wooldridge autocorrelation test results rejected the null hypothesis at a significance level of 1% in Table 3 with respect to coarse particulate matter (PM_{10}) and fine particulate matter ($PM_{2.5}$), panel data regression models had first order autocorrelation. When the heteroscedasticity test results are examined, because the modified Wald test results rejected the null hypothesis and selected the alternative hypothesis when the significance probability (p value) was smaller than 0.01, the existence of heteroscedacity could be determined.

Because Hausman test results rejected the null hypothesis at a significance level of 1% when the significance probability (p value) was smaller than 0.01, the alternative hypothesis was adopted, and a correlation was shown to exist between the individual effect and explanatory variables. Consequently, this study used the more appropriate fixed effect models.

In addition, this study performed natural logarithm transformation of the data. Natural logarithm transformation can reduce the heterogeneity of the data while not modifying the original characteristics of the data. In addition, inconvenience due to disparate measurement units can be eliminated, and the estimated coefficient, which is a coefficient of elasticity, has the advantage of making it possible to interpret an increase of the independent variable by 1% as a change in the pure percentage due to a dependent variable (Liu et al., 2020). Consequently, in this study, panel data regression analysis equation (8) is as follows:

$$\ln Y_{it} = \alpha + \beta_1 \ln U_{it} + \beta_2 \ln C_{it} + \beta_3 \ln S_{it} + \mu_i + \varepsilon_{it} \quad (8)$$

α: constant term
i: (administrative areas): 1, 2, 3… N
t: (time): 1, 2, 3… T
μ_i: individual effect (situation in each city)
ε_{it}: disturbance term

When there are the problems of autocorrelation and heteroscedacity, because the estimator is a consistent estimator but an inefficient estimator and therefore influences the standard error (SE) of the estimated coefficient (β value), it decreases the reliability of the estimated coefficient. Consequently, this study used fixed-effect estimation models employing the Driscoll-Kraay SE correction method, which is more efficient and accurate than pooled OLS (Lian, 2007).

Because the models established above hypothesized that the annual average concentrations of coarse particulate matter (PM_{10}) and fine particulate matter ($PM_{2.5}$) changed according to cities' environmental, social, and economic changes, there was no lagged effect. However, considering that there is actually consistency in changes to cities' environmental, social, and economic elements, past situations can affect the present. Consequently, a lagged effect was confirmed to exist in the annual average concentrations of coarse particulate matter (PM_{10}) and fine particulate matter ($PM_{2.5}$) in disparate areas. In addition, because urban sustainability evaluation indicators for the annual average concentrations of coarse particulate matter (PM_{10}) and fine particulate matter ($PM_{2.5}$) can affect one another, endogenous errors can emerge in the models (Gujarati and Porter, 2009). In order to resolve this problem, this study used dynamic panel models that encompassed lagged variable of dependent variables as explanatory variables along with general static panel models (8). Regression analysis equation (9) is as follows:

$$\ln Y_{it} = \alpha + \lambda \ln Y_{it-1} + \beta_1 \ln U_{it} + \beta_2 \ln C_{it} + \beta_3 \ln S_{it} + \mu_i + \varepsilon_{it} \quad (9)$$

α: constant term
i: (cities): 1, 2, 3... N
t: (time): 1, 2, 3... T
μ_i: individual effect (situation in each city)
ε_{it}: disturbance term
Y_{it-1}: lagged variable of the dependent variable

Because the correlation between lagged variables of dependent variables and the error term cause the problem of endogenous explanatory variables in dynamic panel models, this study used GMM (Allerano and Bond, 1991). In addition, because comparatively large deviation can arise when serial observed values are few in difference GMM, efficient estimators regarding coarse particulate matter (PM_{10}) and fine particulate matter ($PM_{2.5}$) and urban sustainability evaluation indicators were derived using system GMM (Blundell and Bond, 1998; Zheng and Walsh, 2019).

Ⅳ. Results

This study presents in Table 4 the results of dynamic panel model estimation performed through static pane models and system GMM by using the Stata program. First, when the estimation results of static panel models are examined, because Hausman test results reject the null hypothesis at a significance level of 1%, fixed effect models were selected. In addition, because there exist autocorrelation, heteroscedacity, and cross-section correlation, fixed-effect estimation models using the Driscoll-Kraay SE correction method

Table 4. Analysis results

	$PM_{2.5}$ as the depend variable				PM_{10} as the depend variable			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
ln Y_{it-1}				0.7162***				0.8301***
lnYU1	-0.0483	-0.0997**	-0.0997	-0.0513	-0.0549	-0.1118**	-0.1118*	-0.0479
lnU2	-0.0485	-0.0617	-0.0617***	0.0329	-0.0053	-0.0391	-0.0391**	0.0352
lnU3	-1.1578***	-0.6418***	-0.6418***	-0.3510*	-1.1751***	-0.5318***	-0.5318***	-0.1759
lnC1	-0.0865	-0.0080	-0.0080	-0.0089	-0.1046	-0.0505	-0.0505	-0.0207
lnC2	-0.0454	0.0192	0.0192	0.0014	-0.0560	0.0394	0.0394**	-0.0161
lnC3	-0.0246	-0.0429	-0.0429	0.0437	0.0388	-0.0863**	-0.0863**	0.0468
lnS1	-0.1001**	-0.0484	-0.0484**	-0.0490	-0.0748*	0.0177	0.0177	-0.0241
lnS2	-0.0545**	0.0637***	0.0637***	-0.0042	-0.0532**	0.0500***	0.0500***	0.0144
lnS3	0.0507	-0.0037	-0.0037	-0.3071*	0.0597	0.0222	0.0222***	-0.1042
ln_Density	-0.0247	0.0039	0.0039	0.0149	-0.0493	0.0107	0.0107	-0.0111
ln_Commercial	0.0693**	-0.0228	-0.0228***	0.0188	0.0435	-0.0315**	-0.0315*	0.0202
ln_Industrial	0.0169	-0.0279*	-0.0279**	-0.0128	0.0073	-0.0140	-0.0140	-0.0274
ln_Private cars	0.0125	-0.2979***	-0.2979***	0.0546	0.0356	-0.2524***	-0.2524***	0.0355
R-squared	0.7427	0.6924	0.6924		0.7268	0.6362	0.6362	
AR(1)_p				0.061				0.042
AR(2)_p				0.186				0.144
Sargan_p				0.240				0.132
Hansen_p				0.484				0.244

Note1: Significant levels ~p<0.1* ~p<0.05** ~p<0.01***
Note2: Model(1): Pooled OLS; Model(2): Fixed-effect; Model(3): Fixed-effect regression with Driscoll-Kraay standard errors; Model(4): System GMM; Model(5): Pooled OLS; Model(6): Fixed-effect; Model(7): Fixed-effect regression with Driscoll-Kraay standard errors; Model(8): System GMM

were employed. In system GMM estimation, the test results of AR(1) demonstrated the existence of first order correlation with the error term. The test results of AR(2) demonstrated the absence of second order correlation with the error term. The Sargan test and the Hansen test are verification methods for determining the appropriateness of model selection and the validity of instrumental variables. The null hypothesis was adopted at a significance level of 1% according to the test results, and the appropriateness of the models established and the validity of the instrumental variables used in this study were determined. The effect of Chinese cities' sustainability on the improvement of urban air quality according to the results of analysis in Table 4 can be discussed as follows.

First, when the results of analysis on the level of the UEIs are examined, in static panel models (2), (6), and (7), economic quality (U1) exhibited significant negative influence on coarse particulate matter (PM_{10}) and fine particulate matter ($PM_{2.5}$). These results show that the higher the economic quality is, there is a clear inhibition effect on coarse particulate matter (PM_{10}) and fine particulate matter ($PM_{2.5}$) pollution. In addition, this matches the phenomenon of the decoupling of economic growth and environmental pollution (Li et al., 2021), and it can also be confirmed that the atmospheric environment improvement policies currently implemented by the Chinese government are active and effective. In static panel models (3) and (7), social quality (U2) exhibited significant negative influence on coarse particulate matter (PM_{10}) and fine particulate matter ($PM_{2.5}$), and, as for environmental quality (U3), it exhibited significant negative influence in all static panel models. These results match research hypothesis 1-1.

Even when urbanization-based development has a certain degree of negative effects on the atmospheric environment, if the efficiency of urbanization-based development in terms of the economy, society, and environment is high, air quality can be improved. In addition, when the results of calculations with entropy weights on the level of the UEIs (Appendix 1) are examined, the weighted value was the highest for the number of buses per 10,000 people (0.3645), followed by the number of university students per 10,000 people (0.2453), number of physicians per 10,000 people (0.1412), and GDP per capita (0.1350), respectively. the weighted value was the lowest for the urban greening ratio (0.0060). According to these results, discovered was an imbalance between socioeconomic urbanization-based development and environmental urbanization-based development in the urbanization processes of Chinese coastal areas in the last several years. In these areas, socioeconomic urbanization-based development levels tended to be far higher than environmental urbanization-based development levels. Consequently, local governments must further stress the quality of and efficiency in urbanization-based development (Cui et al., 2019). In particular, it is necessary to pay attention to the preservation of urban basic facilities and the improvement of the living environment.

Second, when the results of analysis on the level of the CDIs are examined, in the case of the coordination degree economic and social (C1), none of the models yielded significant results. However, in all models, the coordination degrees of social and economic development exhibited negative correlation coefficients with respect to coarse particulate matter (PM_{10}) and fine particulate matter ($PM_{2.5}$). In panel models (6) and (7), the coordination degree social and environment (C3) exhibited significant positive influence on coarse particulate matter (PM_{10}). These results match research hypothesis 1-2 that the higher the coordination degree is, the more the air quality can be improved.

In static panel model (7), the coordination degree economic and environment (C2) exhibited significant positive influence on coarse particulate matter (PM_{10}). These results explain that, at the present stage, focusing only on the urbanization-based development of the population and land has negative effects on improving coarse particulate matter (PM_{10}) and fine particulate matter ($PM_{2.5}$) pollution. In addition, harmonious economic, social, and environmental development reflects equity, and the results of the analysis of these indicators match the claim of previous research that many urban problems have arisen due to disagreement between the quality and the quantity of China's dramatic urbanization-based development and urbanization (Fang and Liu, 2009). Though the Chinese government has focused on the urbanization of land and economic gain from the sales and purchases of land, neglecting the coordination degrees among the economy, society, and environment in urbanization-based development, it is necessary to focus on improving income inequality in the process of urbanization-based development and building or improving welfare, infrastructures, and quality of life according to the results of this study. In addition, when the results of the calculation of entropy weights on the level of the CDIs (Appendix 1) are examined, the weighted value was the highest for the ratio of the public education expenditure to the GDP (0.3040), the number of wastewater treatment facilities per 10,000 people (0.2762), ratio of urban public facility construction investment costs to the GDP (0.2428), number of waste treatment facilities per 10,000 people (0.1990), and ratio of environmental protection investment costs to the GDP (0.1254), respectively. According to these results, on the level of the coordination degrees of economic, social, and environmental development in coastal Chinese cities, more emphasis was placed on the coordination degree between the economy and the environment. This means that, in improving the local environment, the elimination of pollution sources first is more effective than the “pollution first, elimination afterwards” development method. Consequently, it is necessary for the government to stress further upgrading industrial and environmental protection technologies and to secure better environmental protection along with continued economic growth.

Third, when the results of analysis on the level of the SUIs are examined, in models (1), (3), and (5), sustainable economic urbanization (S1) exhibited significant negative influence on coarse particulate matter (PM_{10}) and fine particulate matter ($PM_{2.5}$). Though the dramatic development of urbanization has led economic growth, in general, the pursuit of high economic profits can neglect the environmental carrying capacity and destroy the ecological environment as well. Because the results of a study arguing that a drop in the quality of economic growth is a major cause of environmental damages (Fang et al., 2015), it is necessary to change industry-optimized upgrading and traditional paradigms of economic development. In the case of sustainable social urbanization (S2), models (2), (3), (6), and (7) exhibited significant positive influence. In addition, in model (7), sustainable economic urbanization (S3) exhibited significant positive influence on coarse particulate matter (PM_{10}). Results on the level of the SUIs according to the results of calculations of entropy weights (Appendix 1) are examined, the weighted value was the highest for the ratio of the scientific and technological researcher expenditure to the development of hi-tech industries to the GDP (X26) (0.4064), followed by the ratio of the financial expenditure for energy saving and environmental protection to the total financial expenditure (X32) (0.2393), ratio of urban residents’ subscription to basic medical insurance (X27) (0.1270), and ratio of the tertiary industry to the GDP (X25) (0.1024), respectively. According to these results, Chinese coastal cities placed more stress on sustainable economic urbanization-based development. Urbanization in China is in the accelerated development stage, and the unilateral emphasized on the speed of urbanization, thus causing an imbalance between the quality and the quantity in urbanization-based development (Fang and Wang, 2011). However, sustainable urbanization-based development can also improve air quality through the adjustment of economic structures such as marketization, globalization, and decentralization and institutional incentives such as local governments’ and corporations’ energy saving incentives (He et al., 2014; Zheng et al., 2017). In addition, out of the results of calculations with entropy weights on the level of the SUIs (Appendix 1), the weighted value was the highest for the ratio of the scientific and technological research expenditure for the development of hi-tech industries to the GDP (0.4064), followed by the ratio of the financial expenditure for energy saving and environmental protection to the total financial expenditure (0.2393), urban residents’ subscription rate to basic medical insurance (0.1270), and ratio of the tertiary industry to the GDP (0.1024), respectively. According to these results, coastal Chinese cities further stressed sustainable economic urbanization-based development. Local governments in these areas not only increased investments for the development of hi-tech industries and the share of the tertiary industry but also made efforts regarding energy saving and environmental protection investments. Consequently, sustainable urbanization does not excessively inhibit urbanization-based development but makes possible continued harmony among urbanization-based development and the environment, resources, society, and economy.

Fourth, when the results of the analysis of dynamic panel models (models 4 and 8) are examined, the annual average coarse particulate matter (PM_{10}) and fine particulate matter ($PM_{2.5}$) pollution concentrations in the past had positive influence on the annual average coarse particulate matter (PM_{10}) and fine particulate matter ($PM_{2.5}$) pollution concentrations in the present. This signifies that the higher the current coarse particulate matter (PM_{10}) and fine particulate matter ($PM_{2.5}$) pollution concentrations are, the higher the coarse particulate matter (PM_{10}) and fine particulate matter ($PM_{2.5}$) pollution concentrations in the next period can be. In addition, the lagged variable of coarse particulate matter (PM_{10}) and fine particulate matter ($PM_{2.5}$) was estimated to have a significance probability of 1%, with the regression coefficient values amounting to 0.8301 and 0.7162, respectively. Therefore, when coarse particulate matter (PM_{10}) and fine particulate matter ($PM_{2.5}$) pollution concentrations increased by 1% in the current period, coarse particulate matter (PM_{10}) and fine particulate matter ($PM_{2.5}$) pollution concentrations could increase by 0.83% and 0.72%, respectively, in the next period. In other words, coarse particulate matter (PM_{10}) and fine particulate matter ($PM_{2.5}$) pollution has continuity, and past pollution can significantly affect the future. In model (4), the environmental quality (U3) and sustainable environmental urbanization (S3) exhibited significant negative influence on fine particulate matter ($PM_{2.5}$). Consequently, air pollution reduction and continued investments in energy saving and environmental protection have important meanings for managing the atmospheric environment in the future. In other words, sustainable urbanization does not excessively inhibit urbanization-based development but makes possible continued harmony among urbanization-based development and the environment, resources, society, and economy.

Finally, when control variables are examined, in models (3) and (7), the areas of industrial zones exhibited negative influence on coarse particulate matter (PM_{10}) and fine particulate matter ($PM_{2.5}$). According to previous research, there exists a causal relationship between industrial development and air pollution, the transition of the secondary industry to the tertiary industry can help to improve air quality (Zhang et al., 2020). The clustering of the industries not only improves efficiency in the use of land and energy but also concentrates pollutants discharged from industrial production, thus further helping pollution treatment. In addition, clustered industrial complexes have a certain effect on saving transportation costs and improving air quality as well. In the estimation results in models (3) and (7), when private automobiles increased by 1%, then coarse particulate matter (PM_{10}) and fine particulate matter ($PM_{2.5}$) pollution concentrations increased by 0.2524% and 0.2979%, respectively. The continued rise in the number of private automobiles because of the development of the economy, urbanization, and transportation in the past several years has increased road areas and population mobility, thus increasing traffic congestion and automobile exhaust gas emissions. Consequently, it is necessary to improve the rational planning of urban transportation spaces and efficiency in the use of urban road resources. In order to mitigate urban traffic congestion, proposed are an increase in investments in public transportation, construction of a smart transportation system, and a green transit method combining walking, bicycles, and public transportation (Stone, 2008; Zang et al., 2017; Wu et al., 2018).

V. Conclusions

This study sought to grasp the effects of urban sustainability on the improvement of urban air quality on the basis of panel data on 46 Chinese coastal cities from 2014-2019. To achieve this, static panel models and dynamic panel models were used to conduct empirical analysis, and, through the results of analysis, the following conclusion was derived, and policy suggestions were presented.

In sum, first, in China's coastal region, the annual average concentrations and urban sustainability levels of coarse particulate matter (PM_{10}) and fine particulate matter ($PM_{2.5}$) exhibited clear spatial differences (Appendix 2). Second, China is experiencing a decoupling phenomenon of economic growth and environmental pollution. According to the study results, the higher the economic quality was, the more reduced was pollution due to coarse particulate matter (PM_{10}) and fine particulate matter ($PM_{2.5}$), and the greater the urban sustainability on the economic, social, and environmental levels was, the more reduced was pollution due to coarse particulate matter (PM_{10}) and fine particulate matter ($PM_{2.5}$). Consequently, the Chinese government must further stress cities' harmonious economic, environmental, and social development, use resources effectively, adjust the quality improvement and development rate of urbanization, and achieve sustainable urban development by improving the environment.

Urbanization in China has stressed the speed of urbanization-based development in a fragmented manner at the stage of accelerated development and caused qualitatively and quantitatively unbalanced development on the basis of urbanization (Fang and Wang, 2011). The quality of urbanization-based development can reflect rationality in urbanization-based development in the provinces, efficiency in economic urbanization, and equity in social urbanization (Xu et al., 2007). Consequently, in order to establish effective urbanization-based development strategies and to promote healthy and orderly sustainable development, it is important to understand and the evaluate coordination between the quality and quantity of urbanization-based development.

The estimation results of the dynamic panel models demonstrated continuity in pollution due to coarse particulate matter (PM_{10}) and fine particulate matter ($PM_{2.5}$). It was confirmed that when past coarse particulate matter (PM_{10}) and fine particulate matter ($PM_{2.5}$) pollution concentrations increased by 1%, current coarse particulate matter (PM_{10}) and fine particulate matter ($PM_{2.5}$) pollution concentrations increased by 0.8301% and 0.7162%, respectively. These results have important implications for Chinese government policies to improve urban air quality and show that a "pollution first, management afterwards" method of managing the environment is not effective. Consequently, the government must perceive that upgrading industrial technology and environment management technology is an effective methods for reducing air pollutant emissions. At the same time, it must legislate air pollution reduction policies, thus emphasizing policy consistency. In particular, because economic and urbanization-based development differs for each area, it is all the more important to implement appropriate management policies tailored to each area. Consequently, this study proposes that air quality improvement and sustainable development must be achieved through effective government monitoring means and incentive mechanisms.

Because cities are complex and vast systems, individual factors can affect one another, thus making it difficult to determine causal relations among factors. In particular, causal relations cannot be confirmed simply when limitations to data collection and the complexity of the influencing factors of air pollution are taken into consideration. In addition, because cities are multidimensional systems and due to accessibility to data and the amount of calculations, this study selected only six-year data for 46 Chinese coastal cities as the research unit. Consequently, necessary in future research are comparative studies that expand the study samples and create a classification in terms of measures per scale and cities per development stage. The theoretical framework of mechanisms for analyzing the effects of individual levels in the measurement of sustainable development levels on air quality improvement must be prepared to be more complete, thus providing a scientific basis for urban planning and development.

Finally, based on the conclusion above, the following is suggested. (1) Development level: According to the study results (Appendix 2), it was discovered that areas with severe air pollution were concentrated in China's eastern coastal region and that air quality in the southeastern and southern coastal regions was relatively good. The southeastern coastal region is known to be concentrated with the hi-tech and tertiary (tourism) industries, and the eastern coastal region was concentrated mostly with the secondary industry. Based on the results of research that rises in technological innovations in the secondary industry and the share of the tertiary industry increase aid the improvement of air quality (Zhang et al., 2020), this study suggest that, by adjusting local industrial structures to be optimal and increasing the share of the tertiary industry, a transition from traditional high-pollution and high-energy production methods to green, low-carbon, and environment-friendly industries must be made. (2) Coordination degree: According to the study results (Appendix 2), the coordination degrees of urban development were very low in all of the areas studied. In particular, the coordination degrees of environmental and economic development were the lowest. In addition, the problem of environmental pollution, especially air pollution, is characterized by being cumulative, long-term, intersectional, and fluid. As for air pollution, with the concentration and expansion of urban economic activities, pollutants pile up and spread and can cause pollution in not only the areas in which they are found but also other, surrounding areas. Consequently, in order to reduce air pollution and to improve air quality, cooperation with surrounding cities, areas, and, furthermore, nations is needed, and differences in local development, too, must be taken into consideration. The integration of urban construction and environmental governance must be realized through minimal resource consumption, and social, economic, and environmental harmony must be promoted through sustainable development. (3) Sustainability level: The sustainability of the environment is the basis of economic development and social progress. According to the study results, the sustainable urbanization levels of the areas studied rose annually, but there were clear differences among the areas in the growth rate. Consequently, resource advantages must be amply used per area, and development policies for urban sustainability appropriate for each area must be legislated. In addition, it is necessary to raise efficiency in resource use, to strengthen the development and use of new energy, to improve energy efficiency and low-carbon/environment-friendly technologies, to increase investments in energy saving and environmental governance, and to establish and to supplement urban environment policies and ecological management systems.

Note 1. Announced in 2021, the WHO's "The Air Quality Guidelines" constituted the first update after the announcement of guidelines in 2005. These new air quality guidelines adjusted the guidelines for $PM_{2.5}$ from 10 ㎍/m³ per year and 25 ㎍/m³ per 24 hours (as of 2005-2020) to 5 ㎍/m³ per year and 15 ㎍/m³ per 24 hours (as of September 2021), respectively. The guidelines for PM_{10} were adjusted from 20 ㎍/m³ per year and 50 ㎍/m³ (as of 2005-2020) per 24 hours to 15 ㎍/m³ per year and 45 ㎍/m³ per 24 hours (as of September 2021), respectively (WHO, 2021).

References

1 Ahmad, M., Zhao, Z.Y., Irfan, M., Mukeshimana, M.C., Rehman, A., Jabeen, G., and Li, H., 2020. "Modeling Heterogeneous Dynamic Interactions Among Energy Investment, SO_2 Emissions and Economic Performance in Regional China", *Environmental Science and Pollution Research*, 27(3): 2730-2744.

2. Alattar, N. and Yousif, J., 2019. "Evaluating Particulate Matter ($PM_{2.5}$ and PM_{10}) Impact on Human Health in Oman Based on a Hybrid Artificial Neural Network and Mathematical Models", paper presented at 2019 International Conference on Control, Artificial Intelligence, Robotics and Optimization (ICCAIRO), Athens: Greece.

3. Alberti, M., 1996. "Measuring Urban Sustainability", *Environmental Impact Assessment Review*, 16(4-6): 381-424.

4. Arellano, M. and Bond, S., 1991. "Some Tests of Specification for Panel Data: Monte Carlo Evidence and An Application to Employment Equations", *The Review of Economic Studies*, 58(2): 277-297.

5. Baumgärtner, S. and Quaas, M., 2010. "What is Sustainability Economics?", *Ecological Economics*, 69(3): 445-450.

6. Blundell, R. and Bond, S., 1998. "Initial Conditions and Moment Restrictions in Dynamic Panel Data Models", *Journal of Econometrics*, 87(1): 115-143.

7. Brunekreef, B. and Holgate, S.T., 2002. "Air Pollution and Health", *The lancet*, 360(9341): 1233-1242.

8. Button, K., 2002. "City Management and Urban Environmental Indicators", *Ecological Economics*, 40(2): 217-233.

9. Cai, Z.B. and Chu, D.T., 2012. "An Evaluation of Urban Sustainable Development Capability: Based on Jiangsu Province", *Urban Insight*, 4: 142-149.

10. Chatterjee, S. and Hadi, A.S., 2006. *Regression Analysis by Example*, New York: John Wiley & Sons.

11. Chen, Y., Jin, G.Z., Kumar, N., and Shi, G., 2013. "The Promise of Beijing: Evaluating the Impact of the 2008 Olympic Games on Air Quality", *Journal of Environmental Economics and Management*, 66(3): 424-443.

12. Cui, X., Fang, C., Liu, H., and Liu, X., 2019. Assessing Sustainability of Urbanization by a Coordinated Development Index for an Urbanization-Resources-Environment Complex System: A Case Study of Jing-Jin-Ji Region, China", *Ecological Indicators*, 96: 383-391.

13. Dempsey, N., Bramley, G., Power, S., and Brown, C., 2011. "The Social Dimension of Sustainable Development: Defining Urban Social Sustainability", *Sustainable Development*, 19(5): 289-300.

14. Dias, N., Curwell, S., and Bichard, E., 2014. "The Current Approach of Urban Design, Its Implications for Sustainable Urban Development", *Procedia Economics and Finance*, 18: 497-504.

15. Fang, C. and Liu, X., 2009. "Temporal and Spatial Differences and Imbalance of China's Urbanization Development during 1950-2006", *Journal of Geographical Sciences*, 19(6): 719-732.

16. Fang, C. and Wang, D., 2011. "Comprehensive Measures and Improvement of Chinese Urbanization Development Quality", *Geographical Research*, 30(11): 1931-1946.

17. Fang, C., Guan, X., Lu, S., Zhou, M., and Deng, Y., 2015. "Input-output Efficiency of Urban Agglomerations in China: An Application of Data Envelopment Analysis (DEA)", *Urban Studies*, 50(13): 2766-2790.

18. Fehr, M., Sousa, K.A., and Pelizer, L.C., 2004. "Proposal of Indicators to Assess Urban Sustainability in Brazil", *Environment, Development and Sustainability*, 6(3): 355-366.

19. Fleischmann, A. and Feagin, J.R., 1987. "The Politics of Growth-oriented Urban Alliances: Comparing Old Industrial and New Sunbelt Cities", *Urban Affairs Quarterly*, 23(2): 207-232.

20. Ge, Y., Lou, I., Zheng, H., and Wang, Z., 2015. "Regional Sustainable Development Assessment for an Air Quality Index System: A Case Study of the Macau Special Administration Region", *Sustainable Development (2 Volume Set)*, 168: 63-72.

21. General Assembly, 2012. *Resolution Adopted by the General Assembly on 27 July 2012*, United Nations: Norfolk, VA, USA.

22. Gujarati, D.N. and Porter, D.C., 2009. Basic Econometrics. 5th edition (5), Boston: McGraw-Hill Irwin.

23. Han, L., Zhou, W., Li, W., and Li, L., 2014. "Impact of Urbanization Level on Urban Air Quality: A Case of Fine Particles (PM2.5) in Chinese Cities", *Environmental Pollution*, 194: 163-170.

24. Han, R., Feng, C.C., Xu, N., and Guo, L., 2020. Spatial Heterogeneous Relationship between Ecosystem Services and Human Disturbances: A Case Study in Chuandong, China, *Science of The Total Environment*, 721: 137818.

25. Harvey, D., 1989. "From Managerialism to Entrepreneurialism: The Transformation in Urban Governance in Late Capitalism", *Geografiska Annaler: Series B, Human Geography*, 71: 3-17.

26. Haughton, G., 1999. "Environmental Justice and the Sustainable City", *Journal of Planning Education and Research*, 18(3): 233-243.

27. Haughton, G. and Hunter, C., 2004. *Sustainable Cities*, London: Routledge.

28. He, C., Huang, Z., and Ye, X., 2014. "Spatial Heterogeneity of Economic Development and Industrial Pollution in Urban China", *Stochastic Environmental Research and Risk Assessment*, 28(4): 767-781.

29. Hosseinabad, E.R. and Moraga, R.J., 2017. "A System Dynamics Approach in Air Pollution Mitigation of Metropolitan Areas with Sustainable Development Perspective: A Case Study of Mexico City", *Journal of Applied Environmental and Biological Sciences*, 7(12): 164-174.

30. Huang, X. and Huang, M.S., 2015. "Relationship between Sustainable Urban Development and Economic Growth based on Energy Analysis: A Case Study of Quanzhou City", *Progress in Geography*, 34(1): 38-47.

31. Huang, Y., Ji, Y., Zhu, Z., Zhang, T., Gong, W., Xia, X., and Chen, D., 2020. "Satellite-based Spatiotemporal Trends of Ambient $PM_{2.5}$ Concentrations and Influential Factors in Hubei, Central China", *Atmospheric Research*, 241: 104929.

32. Jha, R. and Singh, V.P., 2008. "Evaluation of Riverwater Quality by Entropy", *KSCE Journal of Civil Engineering*, 12(1): 61-69.

33. Kang, J.E. and Lee, M.J., 2012. "Assessment of Flood Vulnerability to Climate Change Using Fuzzy Model and GIS in Seoul", *Journal of the Korean Association of Geographic Information Studies*, 15(3): 119-136.
강정은·이명진, 2012. "퍼지모형과 GIS를 활용한 기후변화 홍수 취약성 평가 -서울시 사례를 중심으로-", 「한국지리정보학회지」, 15(3): 119-136.

34. Kim, H.S., Park, G.J., Kim, S.D., Choi, M.H., Park, M.J., and Yoon, J.Y., 2012. "Assessment of Flood Vulnerability Considering Climate Change and Large-scale River Restoration Project", *Journal of Korean Society of Hazard Mitigation*, 12(2): 107-113.

35. Lee, H.Y. and Noh, S.C., 2013. *Advanced Statistical Analysis* (2th ed.), Seoul: Moonwoosa.
이희연·노승철, 2013. 「고급통계분석론」(제2판), 서울: 문우사.

36. Lee, S.H., Kang, J.E., Bae, H.J., and Yoon, D.K., 2015. "Vulnerability Assessment of the Air Pollution using Entropy Weights: Focused on Ozone", *Journal of the Korean Association of Regional Geographers*, 21(4): 751-763.
이상혁·강정은·배현주·윤동근, 2015. "엔트로피 가중치를 활용한 대기오염 취약성 평가: 오존을 중심으로", 『한국지역지리학회지』, 21(4): 751-763.

37. Li, H., Wei, Y.D., and Swerts, E., 2020. "Spatial Inequality in the City-regions in the Yangtze River Valley, China", *Urban Studies*, 57(3): 672-689.

38. Li, M.Y. and Jung, J.C., 2021. "Assessment the Development Level of Urbanization on the Impact of Air Quality Improvement: A Case Study of Provinces and Municipalities Region, China", *Journal of Environmental Policy and Administration*, 29(3): 77-111.
리멍잉·정주철, 2021. "도시화발전수준이 대기질 개선에 미치는 영향에 관한 연구: 중국31 개성·직할시(省·直轄市)를 대상으로", 『환경정책』, 29(3): 77-111.

39. Li, Y., Li, Y., Zhou, Y., Shi, Y., and Zhu, X., 2012. "Investigation of a Coupling Model of Coordination between Urbanization and the Environment", *Journal of Environmental Management*, 98: 127-133.

40. Lin, B. and Ouyang, X., 2014. "Energy Demand in China: Comparison of Characteristics between the US and China in Rapid Urbanization Stage", *Energy Conversion and Management*, 79: 128-139.

41. Liu, S., Zhang, P., Jiang, X., and Lo, K., 2013. "Measuring Sustainable Urbanization in China: A Case Study of the Coastal Liaoning Area", *Sustainability Science*, 8(4): 585-594.

42. Liu, X., Zou, B., Feng, H., Liu, N., and Zhang, H., 2020. "Anthropogenic Factors of $PM_{2.5}$ Distributions in China's Major Urban Agglomerations: A Spatial-temporal Analysis", *Journal of Cleaner Production*, 264: 121709.

43. Liu, Y., Wu, J., and Yu, D., 2017. "Characterizing Spatiotemporal Patterns of Air Pollution in China: A Multiscale Landscape Approach", *Ecological Indicators*, 76: 344-356.

44. Luo, J., Du, P., Samat, A., Xia, J., Che, M., and Xue, Z., 2017. "Spatiotemporal Pattern of $PM_{2.5}$ Concentrations in Mainland China and Analysis of Its Influencing Factors using Geographically Weighted Regression", *Scientific Reports*, 7(1): 1-14.

45. Maclaren, V.W., 1996. "Urban Sustainability Reporting", *Journal of the American Planning Association*, 62(2): 184-202.

46. Malkina-Pykh, I.G., 2002. "Integrated Assessment Models and Response Function Models: Pros and Cons for Sustainable Development Indices Design", *Ecological Indicators*, 2(1-2): 93-108.

47. Maranghi, S., Parisi, M.L., Facchini, A., Rubino, A., Kordas, O., and Basosi, R., 2020. "Integrating Urban Metabolism and Life Cycle Assessment to Analyse Urban Sustainability", *Ecological Indicators*, 112: 106074.

48. Matz, C.J., Egyed, M., Xi, G., Racine, J., Pavlovic, R., Rittmaster, R., and Stieb, D.M., 2020. "Health Impact Analysis of $PM_{2.5}$ from Wildfire Smoke in Canada (2013-2015, 2017-2018)", *Science of The Total Environment*, 725: 138506.

49. Molina-Gómez, N.I., Diaz-Arevalo, J.L., and López-Jiménez,

P.A., 2020. "Air Quality and Urban Sustainable Development: The Application of Machine Learning Tools", *International Journal of Environmental Science and Technology*, 1-18.

50. Namkoong, K., Cho, K.H., and Kim, S., 2017. *Public Administration and Policy in Korea: Its Evolution and Challenges* (Vol. 25), Taylor & Francis.

51. National Bureau of Statistics of China, 2013-2020. *China Statistical Yearbook* (*2013-2020*), China Statistics Press: Beijing, China.

52. Nijkamp, P. and Perrels, A., 2014. *Sustainable Cities in Europe*, Routledge.

53. Nyuk, H.W., Steve, K.J., and Chun, L.T., 2011. "Integrated Urban Microclimate Assessment Method as a Sustainable Urban Development and Urban Design Tool", *Landscape and Urban Planning*, 100(4): 386-389.

54. Omer, A.M., 2007. "Energy, Water and Sustainable Development", in *Sustainable Development Research Advances*, edited by Barton A. Larson, 189-205, New York: Nova Science Pub.

55. Ravetz, J., 2000. "Integrated Assessment for Sustainability Appraisal in Cities and Regions", *Environmental Impact Assessment Review*, 20(1): 31-64.

56. Repetti, A. and Desthieux, G., 2006. "A Relational Indicator-set Model for Urban Land-use Planning and Management: Methodological Approach and Application in Two Case Studies", *Landscape and Urban Planning*, 77(1-2): 196-215.

57. Riley, J., 2001. "Indicator Quality for Assessment of Impact of Multidisciplinary Systems", *Agriculture, Ecosystems and Environment*, 87(2): 121-128.

58. Schell, L.M. and Ulijaszek, S.J., 1999. *Urbanism, Health and Human Biology in Industrialised Countries* (*No. 40*), Cambridge University Press.

59. Shen, L., Zhou, J., Skitmore, M., and Xia, B., 2015. "Application of a Hybrid Entropy-McKinsey Matrix Method in Evaluating Sustainable Urbanization: A China Case Study", *Cities*, 42: 186-194.

60. Song, Y.C., Wang, H., and Xue, J.C., 2016. "Prediction of Environment Sustainable Development of Baotou based on ARIMA-BP-ANN Model", *Resource Development & Market*, 32(2): 156-161.

61. Stone, B. Jr, 2008. "Urban Sprawl and Air Quality in Large US Cities", *Journal of Environmental Management*, 86(4): 688-698.

62. Sun, X., Liu, X.S., Li, F., and Tao, Y., 2016a. "Comprehensive Evaluation of Sustainable Development for Different Scale Cities in China", *Acta Ecologica Sinica*, 3617: 5590-5600.

63. Sun, X., May, A., and Wang, Q., 2016b. "The Impact of User- and System-initiated Personalization on the User Experience at Large Sports Events", *Applied Ergonomics*, 54: 1-9.

64. Tjallingii, S.P., 1995. *Ecopolis: Strategies for Ecologically Sound Urban Development*, Leiden: Backhuys.

65. Tran, L., 2016. "An Interactive Method to Select a Set of Sustainable Urban Development Indicators", *Ecological Indicators*, 61: 418-427.

66. Verdini, G. and Zhang, L., 2020. "Urban China: The Tortuous Path towards Sustainability", *Planning Theory and Practice*, 21(2): 330-336.

67. Walter, B., Arkin, L., and Crenshaw, R.W., 1992. *Sustainable Cities: Concepts and Strategies for Eco-city Development*, Eco-Home Media.

68. Wang, D., Fang, C., Yang, Q., and Li, F., 2010. "Chinese Urbanization Speed Judging Based on Urbanization Quality", *Scientia Geographica Sinica*, 30(5): 643-650.

69. Wang, S. and Guo, S., 2012. "Study on Countermeasures for Sustainable Development of Resource-exhausted Cities", *China Soft Science*, 1: 1-13.

70. Wang, S., Zhou, C., Wang, Z., Feng, K., and Hubacek, K., 2017. "The Characteristics and Drivers of Fine Particulate Matter ($PM_{2.5}$) Distribution in China", *Journal of Cleaner Production*, 142: 1800-1809.

71. Wellenius, G.A., Schwartz, J., and Mittleman, M.A., 2015. *Health and the Environment: Addressing the Health Impact of Air Pollution. Draft Resolution Proposed by the Delegations of Albania, Chile, Colombia, France, Germany, Monaco, Norway, Panama, Sweden, Switzerland, Ukraine, United States of America, Uruguay and Zambia. Sixty-Eighth World Health Assembly*, WHO.

72. WHO, 1996. *The World Health Report: 1996: Fighting Disease, Fostering Development*, World Health Organization.

73. WHO, 2016a. *Ambient (outdoor) Air Quality and Health*.

74. World Bank, 2016. *World Development Report 2016*: *Digital Dividends*, World Bank Publications.

75. Wu, J., Zheng, H., Zhe, F., Xie, W., and Song, J., 2018. "Study on the Relationship between Urbanization and Fine Particulate Matter ($PM_{2.5}$) Concentration and Its Implication in China", *Journal of Cleaner Production*, 182: 872-882.

76. Xu, D., Jiang, X., Pan, J., Liao, Q., Wu, X., and Zou, S., 2007. "Research on the Method of Soil Environment Evaluation under Different Landform on a County-wide Scale--A Case Study of Yizheng City, Jiangsu Province", *Journal of Mountain Science*, 1.

77. Xu, H., 1997. "Population, Resources, Environment and Sustainable Development", *CORE*, 4: 41-43.

78. Yang, B., Xu, T., and Shi, L., 2017. "Analysis on Sustainable Urban Development Levels and Trends in China's Cities", *Journal of Cleaner Production*, 141: 868-880.

79. Yang, Y.F. and Shi, P.J., 2011. "Study on Evaluation of Coordinative Development of Urban Sustainable Development System in Gansu Province", *Economic Geography*, 1.

80. Yang, Z.Y. and Li, P.X., 2018. "Sustainable Development of Urban Agglomeration in China: From Concept to Evaluation", *Journal of Chongqing University*, 24(3): 1-12.

81. Yiftachel, O. and Hedgcock, D., 1993. "Urban Social Sustainability: The Planning of an Australian City", *Cities*, 10(2): 139-157.

82. Zang, X., Zhao, T., Wang, J., and Guo, F., 2017. "The Effects of Urbanization and Household-related Factors on Residential Direct CO_2 Emissions in Shanxi, China from 1995 to 2014: A

Decomposition Analysis", *Atmospheric Pollution Research*, 8(2): 297-309.

83. Zhang, F., Xu, N., Wang, L., and Tan, Q., 2020. "The Effect of Air Pollution on the Healthy Growth of Cities: An Empirical Study of the Beijing-Tianjin-Hebei Region", *Applied Sciences*, 10(11): 3699.
84. Zhang, J.J., Xu, Q., and Wei, Q.Q., 1999. "The Research of Sustainable Urban Development in Foreign Countries", *Geographical Research*, 18(2): 207-213.
85. Zhang, W.M., 2004. "Evaluation of Urban Sustainable Development based on Entropy", *Journal of Xiamen University (Arts and Social Sciences)*, 2: 109-115.
86. Zhang, X.K. and An, X.M., 2011. "Empirical Analysis for Beihai's Capacity of Urban Sustainable Development", *China Population Resources and Environment*, 21(6): 37-43.
87. Zhang, X.T., Yao, N., Zhang, Q., Liu, J.F., and He, J.Q., 2018. "Establishing an Assessment Tool for Chian National Sustainable Communities", *China Population Resources and Environment*, 207(9): 40-51.
88. Zhao, D., Chen, H., Li, X., and Ma, X., 2018. "Air Pollution and Its Influential Factors in China's Hot Spots", *Journal of Cleaner Production*, 185: 619-627.
89. Zhao, Y., Tan, Y., and Feng, S., 2020. "Does Reducing Air Pollution Improve the Progress of Sustainable Development in China?", *Journal of Cleaner Production*, 272: 122759.
90. Zhao, Y., Wang, S., and Zhou, C., 2016. "Understanding The Relation Between Urbanization and The Eco-Environment in China's Yangtze River Delta Using an Improved EKC Model and Coupling Analysis", *Science of the Total Environment*, 571: 862-875.
91. Zheng, S. and Kahn, M.E., 2017. "A New Era of Pollution Progress in Urban China?", *Journal of Economic Perspectives*, 31(1): 71-92.
92. Zheng, W. and Walsh, P.P., 2019. "Economic Growth, Urbanization and Energy Consumption-A Provincial Level Analysis of China", *Energy Economics*, 80: 153-162.
93. Zhou, C., Shi, C., Wang, S., and Zhang, G., 2018. "Estimation of Eco-efficiency and Its Influencing Factors in Guangdong Province based on Super-SBM and Panel Regression Models", *Ecological Indicators*, 86: 67-80.
94. Zou, Z.H., Yi, Y., and Sun, J.N., 2006. "Entropy Method for Determination of Weight of Evaluating Indicators in Fuzzy Synthetic Evaluation for Water Quality Assessment", *Journal of Environmental Sciences*, 18(5): 1020-1023.
95. Cruz, C., Gómez, A., Ramírez, L., Villalva, A., Monge, O., Varela, J., Quiroz, J., and Duarte, H., 2017. "Calidad Del Aire Respecto de Metales (Pb, Cd, Ni, Cu, Cr) Y Relación Con Salud Respiratoria: Caso Sonora, México", *Revista Internacional de Contaminación Ambiental*, 33: 23-34.

   Cruz, C., Gómez, A., Ramírez, L., Villalva, A., Monge, O., Varela, J., Quiroz, J., and Duarte, H., 2017. "Air Quality Regarding Metals (Pb, Cd, Ni, Cu, Cr) and Relationship with Health Respiratory: Case of Sonora, Mexico", *International Journal of Environmental Pollution*, 33: 23-34.
96. CCAS, "Short-Lived Climate Pollutants (SLCPs)", Accessed May 3, 2022. https://www.ccacoalition.org/en/content/short-lived-climate-pollutants-slcps
97. Lian, Y.J., 2007. 7. "Estimation with STATA", https://wendang.xuehi.cn/doc/8ce0e7ecf8c75fbfc77db2fa.html
98. OECD, "Air Pollution Effects", Accessed April 25, 2022. https://data.oecd.org/air/air-pollution-effects.htm
99. UN, "International Day of Clean Air for Blue Skies", Accessed April 28, 2022. https://www.cleanairblueskies.org/did-you-know/frequently-asked-questions-air-pollution
100. WHO, 2016b. "WHO Releases Country Estimates on Air Pollution Exposure and Health Impact", Accessed April 22, 2022. https://www.who.int/en/news-room/detail/27-09-2016-who-releases-country-estimates-on-airpollution-exposure-and-health-impact
101. WHO, 2021. "Ambient (outdoor) Air Pollution", Accessed April 22, 2022. https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health

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Appendix

Appendix 1. Entropy weight of indicators used to evaluate the urban sustainable development level

Indicator	Wight	Primary indicator	Wight
		Urbanization Efficiency Indices (U)	
Economic quality (U1)	0.2232	X1: GDP per capita	0.1350
		X2: Percentage of the secondary and tertiary industry	0.0541
		X3: Energy consumption per unit of GDP	0.0203
		X4: Water consumption per unit of GDP	0.0138
Social quality (U2)	0.9631	X5: Citizen Engel's Coefficient	0.0555
		X6: Urban per capita living space	0.0448
		X7: Urban unemployment rate	0.0389
		X8: Number of college students per 10000 population	0.2453
		X9: Number of doctors per 10000 population	0.1412
		X10: Number of buses per 10000 population	0.3645
		X11: Road areas per capita	0.0730
Environment quality (U3)	0.0345	X12: Discharged of waste water per unit of GDP	0.0069
		X13: Green covered area as % of completed	0.0060
		X14: Proportion of air quality equal to and better than level II	0.0215
		Coordination Degree Indices (C)	
Coordination Degree Economic and Social (C1)	0.0930	X15: Financial expenditure for a social safety net in general public expenditure rate	0.0026
		X16: Financial expenditure for education as a percent of GDP	0.0304
		X17: Real average wage	0.0599
Coordination Degree Economic and Environment (C2)	0.8433	X18: Financial expenditure for municipal infrastructure as a percent of GDP	0.2428
		X19 Total investment in the treatment of environmental pollution as a percent of GDP	0.1254
		X20: Sewage treatment plants per 10000 people	0.2762
		X21: Garbage disposal plants per 10000 people	0.1990
Coordination Degree Social and Environment (C3)	0.0637	X22: Park green areas per capita	0.0545
		X23: Life waste harmless treatment rate	0.0092
		Sustainable Urbanization Indices (S)	
Economy (S1)	0.5251	X24: Sustained economic growth	0.0162
		X25: The share of the Added-value of the tertiary industry in GDP	0.1024
		X26: Expenditure for science and technology as a percent of GDP	0.4064
Society (S2)	0.2018	X27: Percentage of urban residents with basic medical insurance	0.1270
		X28: Social burden coefficient	0.0494
		X29: Average per capita income elasticity	0.0253
Environment (S3)	0.2732	X30: Industrial waste material recycle rate	0.0210
		X31: Treatment rate of industrial effluents	0.0130
		X32: Financial expenditures on energy conservation and environmental protection in general public expenditure rate	0.2393

Appendix 2. Spatial analysis