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Identifying crucial urban form characteristics for reducing pneumonia mortality

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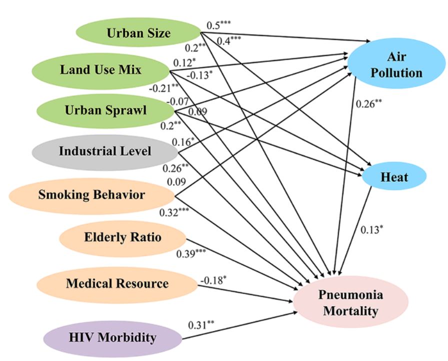
HIGHLIGHTS

- Pneumonia mortality could be mediated by urban form characteristics.
- The minimization of urban size and urban sprawl could lower pneumonia mortality.
- Proper land use mix could reduce pneumonia mortality.
- The industry level of urban function is vital for pneumonia mortality.

GRAPHICAL ABSTRACT



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ABSTRACT

Air pollution and heat pose considerable threats to public health, particularly in urban areas and under the effects of climate change. The well-designed urban form has mediating effects on the atmospheric environment (such as heat and air pollution) and promotes human health. The extant literature has overlooked these mediating effects of urban form on pneumonia mortality. The present study used urban-scale data from 19 counties in Taiwan and partial least squares modeling to identify the crucial effects and pathways of urban form on pneumonia mortality via air pollution and heat. In particular, the model considered the effects of the characteristics of urban form (i.e., urban size, land use mix, and urban sprawl), social situation (i.e., smoking behavior, elderly ratio, and medical resources), and atmospheric environment (i.e., heat and air pollution), as well as urban industry (i.e., industrial level) and disease (i.e., HIV morbidity), on pneumonia mortality. Minimization of urban sprawl and urban size and optimization of land use mix were found to lower pneumonia mortality, and

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minimization of urban size was the most crucial characteristic of urban form correlated with pneumonia mortality. Industrial level, smoking behavior, elderly ratio, medical resources, HIV morbidity, heat, and air pollution also had influences on pneumonia mortality. This is the first study to consider the effects and pathways of urban form characteristics on pneumonia mortality. The findings demonstrate that appropriate planning, design, and policy may reduce pneumonia mortality.

1. Introduction

In 2017, deaths from pneumonia reached approximately 2.6 million worldwide. Global efforts have effectively reduced child pneumonia mortality. However, some countries are currently experiencing sharp rises in adult pneumonia deaths, especially in older adults (JustActions, 2018). Therefore, pneumonia is regarded as a substantial part of the global burden of disease and a public health priority. Pneumonia also results in high socioeconomic losses (WHO, 2019). Multiple studies have reported that pneumonia morbidity and mortality can arise from exposure to air pollutants, such as particulate matter, sulfur dioxide, nitrogen oxide, and carbon monoxide (Cheng et al., 2019; Duan et al., 2016; Ji et al., 2017; Neupane et al., 2010; Sun et al., 2019; Tavallali et al., 2020). Air pollutants impair the function of epithelial cells and alveolar macrophages, increase respiratory epithelial permeability, and further augment the risk of lung infections (Chauhan and Johnston, 2003; Zhou and Kobzik, 2007). Air pollution also suppresses the defensive response of the pulmonary host, potentially leading to the exacerbation of pneumonia (Becker et al., 2003; Michael et al., 2013; Pirozzi et al., 2015; Sawyer et al., 2010).

Ambient temperature is another environmental factor affecting pneumonia, but the evidence on the relationship between the two is mixed (Chen et al., 2019; Davis et al., 2016; Green et al., 2010; Ostro et al., 2010; Qiu et al., 2016; Sun et al., 2019). For example, 2% of emergency hospitalizations for pneumonia in older adults in Hong Kong between 2005 and 2012 were due to hot weather, but 8.7% of the incidences were attributed to cold weather (Qiu et al., 2016). Chen et al. (2019) indicated that cold weather increased the risk of emergency hospitalization for pneumonia in Texas, USA. Davis et al. (2016) noted that cold weather increased pneumonia mortality risk in Auckland, New Zealand. Green et al. (2010) reported that an increase in unlagged mean temperature of 10 °F resulted in a 3.3% increase in pneumonia cases. Moreover, the human body activates its respiratory, sudomotor, and cardiovascular systems to dissipate excess heat upon exposure to heat, thereby increasing the intake of air pollutants (Gordon, 2003). This occurrence may consequently weaken the antibacterial function of lung macrophages and further increase the permeation of bacterial and viral pathogens into the respiratory epithelium, accelerating the development of pneumonia. Furthermore, atmospheric warming affects the transmission of viruses (Donaldson, 2006; Mirsaeidi et al., 2016) and changes the immune response of the host (D'Amato et al., 2015; Dobson, 2009), and thus possibly increase pneumonia morbidity and mortality. These conflicting results demonstrate that the association between temperature and pneumonia remains under debate.

Risk factors for pneumonia include individual characteristics, such as heredity, lifestyle, demographic factors, and the environment (Baskaran et al., 2019; Torres et al., 2013). Of these factors, the environment can be improved—and thus pneumonia mortality can be reduced—through appropriate planning, design, and policymaking. This research focuses on urban form, a critical component of the environment factor, which can be mitigated through those policies and planning.

Urban form refers to the physical characteristics of the built environment, including the shape, density, size, and pattern of city settlements (i.e., land use mix, urban size, and urban sprawl) (Williams, 2014). Urban form largely affects air pollution and heat. Excessive heat and severe air pollution, particularly in urban areas under the impacts of climate change, are harmful to human health. The urban size and population density growth that occurred with urbanization has intensified the urban heat island effect (Kotharkar and Surawar, 2016; Ramirez-Aguilar and Lucas Souza, 2019) and worsened air pollution (Clark et al., 2011; Gezerman and Corbacioglu, 2018; Kang et al., 2019; Lou et al., 2016; Yuan et al., 2018). However, some investigations have reported a reverse outcome regarding the association between population density and air pollutant concentration (Stone, 2008). These inconsistent results indicate that a definite relationship is yet to be established. Other crucial contributing factors to heat and air pollution in cities include urban sprawl and land use mix. Urban sprawl increases commute time, travel distances, and the use of motor vehicles (Cervero and Day, 2008; Ewing et al., 2003a; Gwilliam, 2003; Pucher et al., 2007; Shen, 1997), thereby increasing air pollutants and waste heat. Furthermore, those effects would worsen air pollution and heat (Mohan et al., 2020; Peralta et al., 2019; Pourahmad et al., 2007; Singh and Kalota, 2019; Son and Thanh, 2018; Wang et al., 2019). For example, Pourahmad et al. (2007) indicated that urban sprawl contributed to air pollution in a megacity such as Tehran. Additionally, land use mix ultimately shortens travel distances and promotes the use of public transportation and active transportation (such as walking and cycling) (Cervero, 1996; Cervero and Kockelman, 1997; Lee et al., 2015). These effects could reduce air pollution and heat (Hong and Shen, 2013; Kang et al., 2019; Liu and Shen, 2011). For instance, Kang et al. (2019) reported that the high degree of land use mix is significantly associated with better air quality in Korea.

Urban form plays a vital role on the promotion of well-being. Several studies have noted linkages between health conditions (such as cardiopulmonary disease, obesity, and chronic disease) and urban form through physical activity (Ewing et al., 2003b; Griffin et al., 2013; Rydin et al., 2012; Shen and Lung, 2020). For example, Griffin et al. (2013) reported that land use mix, centeredness, residential density, and street connectivity have considerable effects on improvements in residents' health and that residential density is the most important of the four. The concept of a healthy city places great emphasis on the creation and expansion of physical and social environments, as well as the provision of community resources and opportunities, to maximize resident health (Frank and Engelke, 2001; Northridge et al., 2003; Vlahov et al., 2007). A well-designed urban form has corresponding positive mediating impacts on air pollution and heat reduction. Such a form also increases physical activity levels. All these effects are beneficial to human health. Nevertheless, previous studies have overlooked the mediating effects of urban form on pneumonia mortality through air pollution improvements and heat reduction. Therefore, the present study concentrates on the mediating effects of urban form on pneumonia mortality.

Urban form has substantial impacts on air pollution and heat (Clark et al., 2011; Gezerman and Corbacioglu, 2018; Kang et al., 2019; Kotharkar and Surawar, 2016; Liu et al., 2019; Lou et al., 2016; Ramirez-Aguilar and Lucas Souza, 2019; Son and Thanh, 2018; Stone, 2008; Yuan et al., 2018), and some studies have reported individual associations of air pollutants, heat, industrial level, smoking behavior, age, HIV morbidity, and medical resources with pneumonia mortality (Almirall et al., 2017; Baskaran et al., 2019; Chai et al., 2020; Chang and Kim, 2019; Cheng et al., 2019; Duan et al., 2016; Feldman and Anderson, 2013; Green et al., 2010; Ji et al., 2017; McAllister et al., 2019; Neupane et al., 2010; Ostro et al., 2010; Qiu et al., 2016; Sun et al., 2019; Tavallali et al., 2020; Torres et al., 2013). Therefore, the present objectives were to quantify the impacts of and delineate the routes through which characteristics of urban form (i.e., urban size, land use mix, and urban sprawl), urban industry (i.e., industrial level), social situation (i.e., smoking behavior, the elderly ratio, and medical resources), disease (i.e., HIV morbidity), and atmospheric environment (i.e., air pollution and heat) interact with pneumonia mortality. The direct and indirect mediating effects of the atmospheric environment on pneumonia mortality were also discussed. Furthermore, factors of urban form related to the reduction of pneumonia mortality were identified. An empirical model was constructed using urban-scale data from 19 counties in Taiwan and validated through partial least squares (PLS) modeling. This methodology can be applied to studies on the evaluation of urban form in other countries to formulate practical strategies to mitigate pneumonia mortality.

2. Method and data

2.1. Method

The present study used PLS modeling to determine the relationships among urban form, urban industry, social situation, disease, atmospheric environment, and pneumonia mortality. PLS analysis is a type of structural equation modeling and a component-based estimation approach through which the relationships between multiple variables are examined using an outer and inner model, respectively. The relationships between the latent and observed variables and between the exogenous and endogenous latent variables are analyzed in the outer and inner models, respectively. The present study was focused on the estimation of the endogenous latent variables, which was identified using the exogenous latent variables in the inner model. Because the inputs of independent and dependent variables were standardized, so were the estimate of the total effect and path coefficient. These coefficients, which represent impacts from different variables, can be compared. The unitless standardized path coefficient refers to the degree of change in the standard deviation of an endogenous latent variable attributed to a change of one standard deviation in an exogenous latent variable. The total effect, which is also unitless, denotes the sums of all standardized path coefficients with similar statistical meanings. PLS algorithms and methodology have been described previously (Esposito Vinzi et al., 2010; Hair et al., 2014). In the present study, SmartPLS (SmartPLS GmbH, Bönningstedt, Germany) was used to construct the PLS model, verify its collinearity, reliability, and validity, and analyze the data.

2.2. Indicators

Table 1 presents the latent and observed variables in the PLS model, which were classified into six categories: urban form, urban industry, social situation, disease, atmospheric environment, and pneumonia mortality. Because urban size, land use mix, and urban sprawl are closely correlated with heat, air pollution, and human health (Clark et al., 2011; Lee, 2020; McCarty and Kaza, 2015; Rydin et al., 2012), these latent variables were placed into the urban form category. The latent variable of urban size was quantified by the observed variables of average annual urban population and the urban land area. The entropy index and sprawl index represented the latent variable of land use mix and urban sprawl, respectively. The entropy index evaluates the level of land use mix by calculating the proportion of different land use types, whereas the sprawl index evaluates the level of urban sprawl by calculating the percentages of high and low population density. Supplementary Material A.1 provides detailed formulas on entropy index (Manaugh and Kreider, 2013) and sprawl index (Lopez and Hynes, 2003). Urban industry, an essential contributing factor to health and air pollution alongside urban form (Kohlhammer et al., 2007; Tian et al., 2019; Wang and Chau, 2013), refers to the level of industrialization in a specific county (as determined by the observed variables of the scale and number of factories).

Social situation (i.e., smoking behavior, elderly ratio, and medical resources), disease (i.e., HIV morbidity), and atmospheric environment (i.e., heat and air pollution) have substantial impacts on pneumonia mortality (Almirall et al., 1999; Almirall et al., 2017; Chai et al., 2020; Chang and Kim, 2019; Feldman and Anderson, 2013; McAllister et al., 2019; Theodoratou et al., 2014; Torres et al., 2013). The social situation category comprised three latent variables (i.e., smoking behavior, the elderly ratio, and medical resources), which were indicated by the adult smoking rate, aging population rate, hospital bed ratio, and medical personnel ratio. Atmospheric environment included the latent variables of heat and air pollution. As Taiwan has a subtropical climate with a hot summer, mild winter, and high humidity year-round, this research only focuses on the analysis of heat/high temperature. Heat was measured as the annual mean of the daily maximum temperature. Air pollution refers to the average annual levels of various air pollutants, such as sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen oxide (NO_X), and particles matter with a diameter of<2.5 μm ($PM_{2.5}$). HIV morbidity was the latent variable of disease, and the corresponding observed variable was the number of HIV-infected persons. Pneumonia mortality, a latent variable, refers to pneumonia death rates as defined using the codes in the *International Statistical Classification of Diseases and Related Health Problems, 10th Revision* (ICD-10).

Table 1
Latent and observed variables in the partial least squares model.

Characteristics	Latent variables	Observed variables
Urban Form	Urban Size	• Average annual urban population • Urban land area
	Land Use Mix	• Entropy index
	Urban Sprawl	• Sprawl index
Urban Industry	Industrial Level	• Scale and number of factories
Social Situation	Smoking Behavior	• Adult smoking rate
	Elderly Ratio	• Aging population rate
	Medical Resources	• Hospital bed ratio • Medical personnel ratio
Disease	HIV Morbidity	• Number of HIV-infected persons
Atmospheric Environment	Heat	• Mean annual daily maximum temperature
	Air Pollution	• Average annual levels of SO_2 • Average annual levels of CO • Average annual levels of NO_x • Average annual levels of $PM_{2.5}$
Pneumonia Mortality	Pneumonia Mortality	• Death rates for pneumonia

2.3. Data

This study included 19 counties in Taiwan, the total and average area of which is approximately 35886.9 and 1888.8 ± 1316.3 km^2, respectively (MOI, 2020). The population density of counties ranges from 61.2 to 9574.8 people/km^2, with an average of 1653.5 ± 2339.2 people/km^2 (MOI, 2020). Compared with Western cities/counties, counties in Taiwan have higher degrees of land use mix that are comparable to that in other cities or urban areas in other Asian countries (Abdullahi et al., 2015; Shi and Yang, 2015). Notably, urban form exhibits variations by the level of development in these counties.

All the data for the PLS model analysis were dated from 2005 to 2017, and the sample size is 247. The data for the observed variables of urban form and urban industry were collected from the database of the Directorate General of Budget, Accounting and Statistics. The data on elderly ratio and medical resources were sourced from the database of the Ministry of the Interior. The air pollution and weather parameter data were from 56 Environmental Protection Administration stations and 55 Central Weather Bureau sites (Fig. 1), respectively. A few counties had missing data on weather parameters, so this study adopted the ordinary kriging to estimate the temperature parameters with values measured at stations located in other counties and summed up those estimated parameters to obtain the value within counties. Data for the observed variables of smoking behavior, HIV morbidity, and pneumonia mortality were sourced from the database of the Ministry of Health and

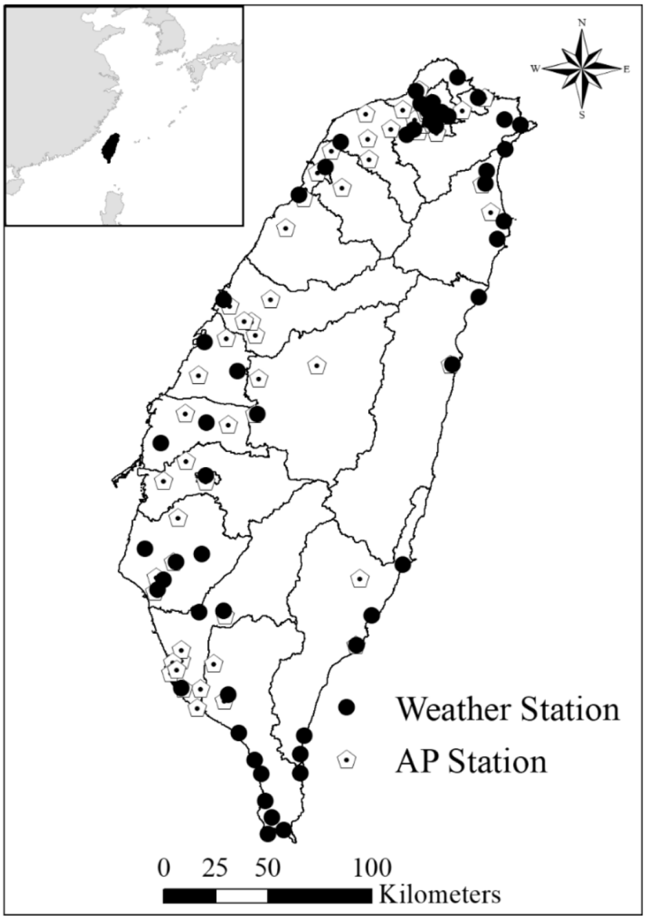

Fig. 1. The location of air pollution and weather stations at nineteen counties in Taiwan.

Table 2
Descriptive statistics of the observed variables in the partial least squares model.

Observed variables	Mean	Standard deviation	Maximum	Minimum
Average annual urban population (persons)	9.67×10^5	1.04×10^6	3.79×10^6	1.29×10^5
Urban land area (km^2)	240.2	278.2	1249	44.4
Entropy index	0.8	0.03	0.9	0.7
Sprawl index	75.3	8.7	98.5	52.6
Scale and number of factories (NT$10,000,000)	4.7×10^{11}	8.06×10^{11}	4.19×10^{12}	3.87×10^7
Adult smoking rate (%)	19.4	3.98	33.5	9.8
Aging population rate (%)	12.2	2.3	18.5	7.1
Hospital bed ratio (%) (number of hospital beds/ per 10,000 population)	73.8	26	153.6	32.7
Medical personnel ratio (%) (persons/per 10,000 population)	105.8	36.2	236.3	51.1
Number of HIV-infected persons (persons)	119	145	591	5
Mean annual daily maximum temperature (°C)	30.1	1.4	33.9	23.1
Average annual levels of SO_2 (ppb)	3.4	1.2	9.4	1.2
Average annual levels of CO (ppm)	0.4	0.09	0.8	0.3
Average annual levels of NO_x (ppb)	19.9	6	40.7	7.9
Average annual levels of $PM_{2.5}$ (μg/m^3)	35	12.9	98.1	13
Overall death rates for pneumonia (per 100,000 population)	37.6	14.9	71.4	14
Female death rates for pneumonia (per 100,000 population)	27.8	12.8	66.1	8.7
Male death rates for pneumonia (per 100,000 population)	47.1	18.2	91.5	17.3

Welfare. In addition to constructing the PLS model through 247 samples, 10,000 samples were resampled through the bootstrap method for testing the robustness of the model. A total of 200 samples were randomly selected every time and sampling was conducted for 50 times to generate a large sample size (10,000 samples) for verifying the PLS model. Table 2 presents the descriptive statistics of the observed variables in the model.

3. Results

3.1. Evaluation of the PLS model

In total, three models of pneumonia mortality were constructed: overall, female, and male. The model evaluation results (including reliability, validity, and collinearity diagnosis) are shown in Supplementary Tables A. 2-1, 2-2, and 2-3, respectively. The latent variables exhibited satisfactory internal consistency, as indicated by the Cronbach's alpha and composite reliability (CR) of each variable exceeding the threshold of 0.7 for construct reliability (Fornell and Larcker, 1981; Hulland, 1999). In addition, discriminant validity for differentiating among the latent variables was demonstrated by the average variance extracted (AVE) for each latent variable being greater than the correlation coefficients among the variables (Esposito Vinzi et al., 2010). Given that the square roots values of the AVE values and the composite reliability of the latent variables exceeded 0.5 and 0.7, respectively, the PLS model had adequate convergent validity (Fornell and Larcker, 1981; Tabachnick and Fidell, 2001). Additionally, the variance inflation factors (VIFs) of the outer and inner models diagnose the collinearity of the observed and latent variables, respectively. According to the results (Table A. 2-1 [B] and [C]), all VIFs of observed and latent variables are<5, an outcome which indicates a lack of collinearity of variables in the outer and inner models.

The goodness of fit (GoF) index of the full PLS model was 0.66 and is greater than the 0.36 which indicates a large effect size in PLS modeling (Wetzels et al., 2009). Thus, the PLS model is plausible and parsimonious. The results of the model constructed based on the 10,000 resamples and 247 samples are consistent, thereby indicating that the PLS model is robust. The explanatory power (R^2) of urban form, social situation, urban industry, disease, and atmospheric environment for pneumonia mortality in the full PLS model was 0.77. As detailed in Supplementary Tables A. 2-2 and 2-3, the models of pneumonia mortality in female and male individuals also fulfilled the model evaluation criteria. That is, both models had adequate discriminant and convergent validity, internal consistency, construct reliability, non-collinearity, and GoF. The explanatory power of these models were 0.75 and 0.77, respectively.

3.2. Path diagrams

Path diagrams of urban form (i.e., urban size, land use mix, and urban sprawl), urban industry (i.e., industrial level), social situation (i.e., smoking behavior, elderly ratio, and medical resources), disease (i.e., HIV morbidity), and atmospheric environment (i.e., heat and air pollution) with pneumonia mortality were constructed through PLS modeling (Fig. 2). In the outer model, the relationships between the latent and observed variables were represented by the paths and loadings. The significant relationships ($p < 0.01$) and the fact that all the loadings exceeded 0.7 demonstrates that the observed variables closely captured the nature of the latent variables. For example, the average

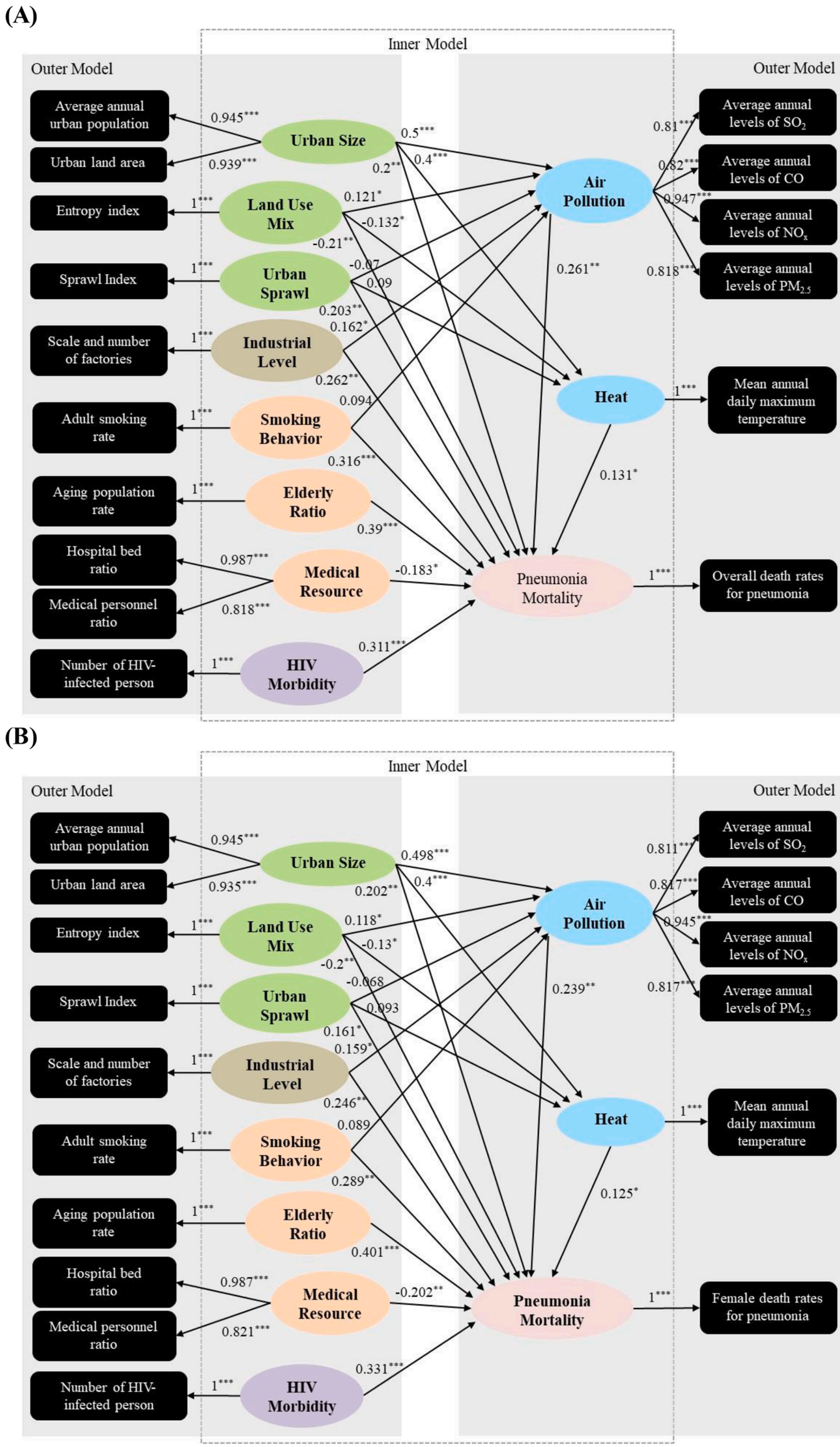

Fig. 2. Path diagrams of urban form, social situation, urban industry, disease, and atmospheric environment with pneumonia mortality. (A) Overall pneumonia mortality. (B) Pneumonia mortality in female individuals. (C) Pneumonia mortality in male individuals. Note: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

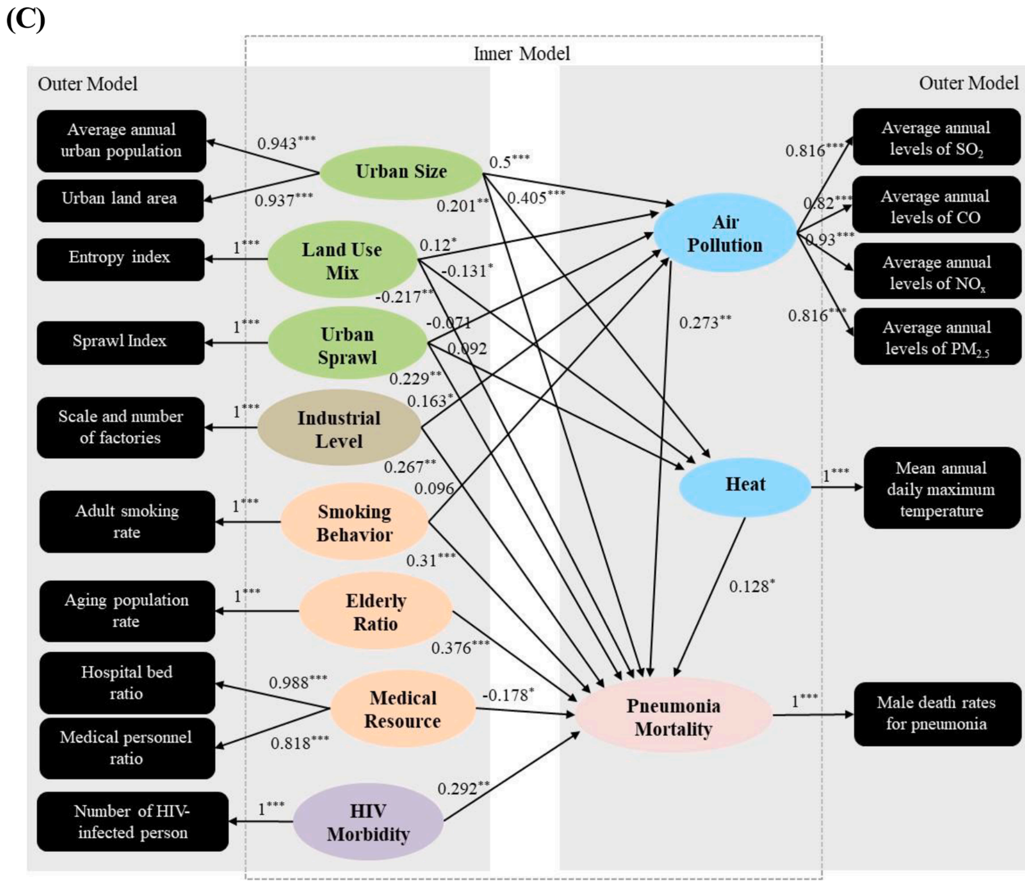

Fig. 2. (*continued*).

annual urban population and urban land area (which represented urban size) had loadings of 0.945 and 0.939, respectively. In other words, they were accurate indicators of urban size, with average annual urban population being the more representative of the two according to the loading level.

In the inner model, the relationships between the latent variables were explained by the paths and the corresponding standardized path coefficients. Regarding the relationship between urban form and pneumonia mortality, land use mix directly negatively affected pneumonia mortality (land use mix $^{(-0.21)}$ > pneumonia mortality). Both urban size and urban sprawl had direct positive effects on pneumonia mortality, with path coefficients of 0.2 and 0.203, respectively. As for indirect effects, urban size and land use mix affected pneumonia mortality through air pollution (i.e., urban size $^{(0.5)}$ > air pollution $^{(0.261)}$ > pneumonia mortality) and heat (i.e., urban size $^{(0.4)}$ > heat $^{(0.131)}$ > pneumonia mortality).

Industrial level exerted direct positive effects on pneumonia mortality, with a path coefficient of 0.262. Moreover, it affected pneumonia mortality through air pollution (i.e., industrial level $^{(0.162)}$ > air pollution $^{(0.261)}$ > pneumonia mortality). Smoking behavior, elderly ratio, HIV morbidity, air pollution, and heat all had direct positive effects on pneumonia mortality, as indicated by coefficients of 0.316, 0.39, 0.311, 0.261, and 0.131, respectively. By contrast, medical resources as directly negatively related to pneumonia mortality (- 0.183).

The pathways and effects of the models of pneumonia mortality in female and male individuals are presented in Fig. 2(B) and (C). Although the path coefficients in those models differed from those in the full model, the significant factors and pathways are consistent. Note that the path coefficient of urban sprawl to female pneumonia mortality is significantly lower than that of male pneumonia mortality. The total effects of urban form, urban industry, social situation, disease, and atmospheric environment on pneumonia mortality are described in the subsequent subsection.

3.3. Total effects

The unitless total effects in Table 3 were computed using standardized path coefficients. In the full model, the indicators that significantly affected pneumonia mortality were urban size, land use mix, urban sprawl, industrial level, smoking behavior, elderly ratio, medical

Table 3
Total effects of urban form, social situation, urban industry, disease, and atmospheric environment with pneumonia mortality.

Exogenous latent variable	Endogenous latent variable		
	Full model with total PM[a]	Female model with female PM[a]	Male model with male PM[a]
Urban Form			
Urban size	0.38^{***}	0.37^{***}	0.39^{***}
Land use mix	-0.2^{**}	-0.19^{**}	-0.2^{**}
Urban Sprawl	0.2^{**}	0.16*	0.22^{**}
Urban Industry			
Industrial Level	0.31^{***}	0.28^{**}	0.31^{***}
Social Situation			
Smoking Behavior	0.34^{***}	0.31^{***}	0.34^{***}
Elderly Ratio	0.39^{***}	0.4^{***}	0.38^{***}
Medical Resources	−0.18*	-0.2^{**}	−0.18*
Disease			
HIV Morbidity	0.31^{***}	0.33^{***}	0.29^{**}
Atmospheric Environment			
Heat	0.13*	0.13*	0.13*
Air Pollution	0.26^{**}	0.24^{**}	0.27^{**}

Note: [a]·PM: Pneumonia mortality; $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

resources, HIV morbidity, heat, and air pollution. With respect to the total effect of urban form on pneumonia mortality, land use mix reduced pneumonia mortality considerably, whereas high urban sprawl and large urban size tended to increase it, as did industrial level.

Social situation (such as elderly ratio and medical resources), disease, and atmospheric environment had only direct effects; therefore, the total effects were equal to the path coefficients. Smoking behavior, elderly ratio, HIV morbidity, heat, and air pollution all contributed to increasing pneumonia mortality, whereas abundant medical resources were related to reductions. Comparable to the results in the full model, the indicators were significant in both mortality models for female and male individuals. Although the total effects differed from those in the full model, the significant indicators were consistent. Notably, the total effect of urban sprawl on pneumonia mortality in the male model is greater than that in the female model.

4. Discussion

The mediating effects that were noted indicated that urban form contributed critically to pneumonia mortality. This research identified the effects and pathways among characteristics of urban form (i.e., urban size, land use mix, and urban sprawl), urban industry (i.e., industrial level), social situation (i.e., smoking behavior, elderly ratio, and medical resources), disease (i.e., HIV morbidity), as well as atmospheric environment (i.e., air pollution and heat) and pneumonia mortality. Minimization of urban size and urban sprawl and maximization of land use mix were the crucial characteristics of urban form that were correlated with reductions in pneumonia mortality, with minimization of urban size being the most influential. Additionally, this research constructed three models (full, female, and male models) to analyze their respective pathways and effects to ascertain whether different genders have different influential pathways and effects. The significant factors in all three models were consistent. The only differences were the variations in the coefficients, especially in the coefficients of urban sprawl to pneumonia mortality.

Large urban size contributes to high density of population and activities, which in turn substantially increases the severity of the urban heat island effect (Kotharkar and Surawar, 2016; Ramirez-Aguilar and Lucas Souza, 2019) and exacerbates air pollution (Clark et al., 2011; Gezerman and Corbacioglu, 2018; Kang et al., 2019; Lou et al., 2016), threatening public health. In the present study, urban heat islands and serious air pollution were found to result from large urban size and further increase pneumonia mortality. Urban sprawl causes inefficient leapfrog development and increases both air pollution (Bereitschaft and Debbage, 2013; Huang and Du, 2018; Liu, 2019) and heat (Liang et al., 2020; Mohan et al., 2020). Although urban sprawl in Taiwan was unlike that in Western cities, it constituted a severe threat with regard to air pollution and heat and in turn increased pneumonia mortality. Moreover, the effect of urban sprawl on pneumonia mortality varies with gender. The influence in males is greater than in female. The employment rate of women in Taiwan is lower than that of men, and Taiwanese women seldom perform long-distance activities (such as long-distance shopping and commute). Thus, the effect of urban sprawl on female pneumonia mortality is significantly lower than that on the male counterpart.

Land use mix was also correlated with pneumonia mortality, and its potential mechanisms include two approaches. First, a high degree of land use mix would reduce travel distance and further lower residents' sedentary driving behavior. Moreover, land use mix would also promote residents' use of active transportation (such as walking and biking). Therefore, the aforementioned influences would increase residents' physical activity, improve residents' cardiopulmonary function, and further reduce the pneumonia mortality. In this study, the direct effect of land use mix on reducing pneumonia mortality showed this consistency. Second, land use mix would reduce the use of motor vehicles, a factor which would decrease air pollutants and waste heat. Furthermore, land use mix would reduce pneumonia mortality through the mediating effects of lowering the air pollution and heat. That is, the indirect pathways and effects are shown in this study; however, inconsistent findings were found on the mediating effects of air pollution. Therefore, the land use mix would increase pneumonia mortality through exacerbating air pollution. Unlike most cities in the United States, many Taiwanese counties have high degrees of land use mix. Some land uses (such as temples, restaurants, cottage industries, and stores) are community pollution sources (Lung et al., 2014). Moreover, the pollutants of community sources exacerbate air pollution. Land use mix thus increased pneumonia mortality through an indirect pathway: it led to an exacerbation of air pollution, which, in turn, increased mortality. Finally, according to the total effect (i.e., the sum of the direct and indirect effects), this study indicated that high land use mix lowered pneumonia mortality, with the impact of the direct effect greater than that of the indirect effect. Additionally, land use mix should be appropriate to ensure that mortality from the mediating effects of air pollution is reduced rather than increased. For example, commercial and residential functions can be combined.

Air pollution is a critical contributing factor to mortality from pneumonia and respiratory diseases (Cheng et al., 2019; Duan et al., 2016; Ji et al., 2017; Kassomenos et al., 2008; Neupane et al., 2010; Sun et al., 2019; Tavallali et al., 2020). Chauhan and Johnston (2003) and Zhou and Kobzik (2007) have indicated that air pollutants impair the function of epithelial cells and alveolar macrophages, increase respiratory epithelial permeability, and further increase the risk of lung infections. Air pollution also suppresses the defensive response of the pulmonary host, potentially leading to exacerbation of pneumonia (Becker et al., 2003; Michael et al., 2013; Pirozzi et al., 2015; Sawyer et al., 2010). To dissipate excess heat upon exposure to heat, the human body activates the respiratory, sudomotor, and cardiovascular systems, increasing the intake of air pollutants (Gordon, 2003). This may in turn weaken the antibacterial function of lung macrophages and further increase the permeation of bacterial and viral pathogens into the respiratory epithelium, accelerating the development of pneumonia. Furthermore, atmospheric warming affects the transmission of viruses (Donaldson, 2006; Mirsaeidi et al., 2016) and changes the immune response of the host (D'Amato et al., 2015; Dobson, 2009), thereby possibly increasing air pollution–related morbidity and mortality. The present findings that air pollution and heat each positively contributed to pneumonia mortality are consistent with those of multiple studies (Cheng et al., 2019; Duan et al., 2016; Ji et al., 2017; Neupane et al., 2010; Ostro et al., 2010; Pirozzi et al., 2015; Sun et al., 2019; Tavallali et al., 2020). Moreover, air pollution and heat were considered, and the extent of their individual influences were compared. The empirical results confirmed the impacts of air pollution and heat on pneumonia mortality in the examined counties. On the basis of the fact that air pollution had a greater effect on pneumonia mortality than heat (0.26 vs. 0.13; Table 3), the mediating effects of urban form on pneumonia mortality are mainly due to reductions in air pollution. Therefore, proper design of urban form is the optimal strategy for attenuating the negative effects of air pollution on human health.

Regarding the linkages of social situation and disease, smoking behavior, elderly ratio and HIV morbidity were positively correlated with pneumonia mortality, whereas medical resources were negatively related to it. Almirall et al. (2017) noted that smoking behavior is one of the main risk factors for pneumonia and determined its severity. In an earlier study, it had been determined that this risk is directly related to the number of cigarettes smoked (Almirall et al., 1999). McAllister et al. (2019), Feldman and Anderson (2013), and Theodoratou et al. (2014) have established that HIV is also a strong risk factor for pneumonia, especially in children. In studies by Feldman and Anderson (2013) and McAllister et al. (2019), pneumonia mortality was high in people with HIV infections; also, permanent decline in lung function was observed. Torres et al. (2013) demonstrate a high risk of pneumonia mortality among older adults, a population among which rates of illness are higher in general. Soares (2007) indicated that medical resources and relevant target projects, vaccination campaigns, and the dissemination of disease prevention knowledge have substantial effects on public health. The sufficiency of medical resources lowers mortality from various diseases and thus has positive impacts on health (Chai et al., 2020; Chang and Kim, 2019). This may explain the impacts of disease (i.e., HIV morbidity) and social situation (i.e., smoking behavior, elderly ratio, and medical resources) on pneumonia mortality observed in the present study.

The present study has several strengths. First, with regard to mediating effects, this investigation is the first to explore the contributions of urban form to pneumonia mortality. Second, the complex relationships and effects among urban form, urban industry, social situation, disease, and atmospheric environment on pneumonia mortality were considered and analyzed simultaneously. Finally, the crucial factors correlated with reductions in pneumonia mortality were determined, in particular the characteristics of urban form, which can be improved through proper planning, design, and policy.

The first limitation of this research is that nonlinear relationships between the variables were not analyzed by PLS modeling. Second, this study used ordinary kriging interpolation to estimate values in certain counties for which data were missing. The estimated values may not be exactly equal to the true data and might have slight influence on the results. Third, the local lifestyle (such as residents' physical activity) affects pneumonia mortality. Moreover, the local lifestyle and urban form / built environment involves interaction. In particular, the type, duration, and intensity of physical activity would be influenced by the characteristics of the urban form / built environment (McCormack, 2017; Sallis et al., 2016). However, given the lack of countywide census data on physical activity, this study cannot clarify the effects of physical activity. Another limitation is that this research only obtained countywide data. Thus, the influences of different spatial scales (such as community) within the county could not be analyzed.

The present study demonstrated the significance of certain characteristics of urban form in reducing pneumonia mortality. The public and policymakers alike should be made aware of the health benefits of minimizing urban size and urban sprawl and maximizing appropriate land use mix. After awareness is achieved, people may be motivated to achieve these goals. In addition, PLS is a useful method to evaluate total effects and relative value of pathways of significant factors on mortality outcomes; therefore, PLS could be further used to analyze the complex relationships among other health or mortality outcomes and their determinants.

5. Conclusions

The present study is the first to not only evaluate how urban form affects pneumonia mortality through mediating effects but also identify the crucial indicators of the healthy city through empirical PLS analysis. The results demonstrate that appropriate policies and urban planning may reduce pneumonia mortality. In particular, the key influencing characteristics of urban form that resulted in these reductions were the maximization of land use mix and the minimization of urban size and urban sprawl, with the minimization of urban size being the most influential characteristic. Smoking behavior, elderly ratio, medical resources, HIV morbidity, heat, air pollution, and industrial level were also significant factors. The present findings can serve as a foundation on which healthy cities can be built and as a guide by which public health and high-quality living environments can be promoted and improved. In addition to providing a unique perspective, using PLS in the context of research on this topic was new. Because PLS modeling can be used to delineate pathways and examine both direct and indirect effects simultaneously, it is suitable for analyzing complex relationships in environmental issues and public health and for determining the influential factors. This approach can be applied to future studies of environmental health.

CRediT authorship contribution statement

Yu-Sheng Shen: Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Shih-Chun Candice Lung:** Investigation, Data curation, Writing - review & editing. **Xingxing Zhai:** Software, Formal analysis, Investigation, Data curation. **Xialu Wu:** Software, Formal analysis, Investigation, Data curation. **Shenghui Cui:** Software, Validation, Formal analysis, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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