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Review article

Deep learning for air pollutant concentration prediction: A review

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HIGHLIGHTS

- The review highlights deep learning methods for air pollutant prediction.
- Datasets and auxiliary features used by air pollution prediction methods are listed.
- We compare experiments in air pollutant prediction and draw some conclusions.
- We summarize the limitations and directions of deep learning-based methods.

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ABSTRACT

Air pollution has become one of the critical environmental problem in the 21st century and has attracted worldwide attentions. To mitigate it, many researchers have investigated the issue and attempted to accurately predict air pollutant concentrations using various methods. Currently, deep learning methods are the most prevailing ones. In this paper, we extend a comprehensive review on deep learning methods specifically for air pollutant concentration prediction. We start from the analysis on non-deep learning methods applied in air pollutant concentration prediction in terms of expertise, applications and deficiencies. Then, we investigate current deep learning methods for air pollutant concentration prediction from the perspectives of temporal, spatial and spatio-temporal correlations these methods could model. Further, we list some public datasets and auxiliary features used in air pollutant prediction, and compare representative experiments on these datasets. From the comparison, we draw some conclusions. Finally, we identify current limitations and future research directions of deep learning methods for air pollutant concentration prediction. The review may inspire researchers and to a certain extent promote the development of deep learning in air pollutant concentration prediction.

1. Introduction

Air pollution, one of our eras greatest misfortunes (Song and Stettler, 2022), has progressively increased climate crisis, and exacerbated environmental degradation (Yousef et al., 2011). Air pollutants have posed great threats on public and individual health (Chen and Chen, 2021): people exposed to contaminated air are more likely to get respiratory and cardiovascular diseases (Kampa and Castanas, 2008; Han et al., 2017). Accurate prediction of air pollutant concentration are of great significance for strategies to control and limit air pollution, and for

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better human health and environmental management (Zheng et al., 2013).

1.1. Challenges

In most studies, air pollutants refer to a mixture of particles and gaseous materials, including, SO_2, $PM_{2.5}$, PM_{10}, NO_2, CO, and O_3 (Wu and Lin, 2019). Prediction on their concentrations is challenging, and usually affected by the following factors.

- Concentrations of pollutants contain complex correlations in both temporal and spatial dimensions, and the correlation of each dimension are dynamically changing.

Dynamic spatial correlation Researchers generally treat air pollutant concentration prediction as a single-site prediction problem. Existing studies have demonstrated that pollutant concentrations are affected by other factors and diffuses between sites, including geographic locations and meteorological conditions, like temperature, humidity, wind direction, etc. For example, there are two neighboring sites in a region with a north-south distribution. If the wind is blowing from the south, we can predict that the air pollutant concentration at the northern site will increase (Pak et al., 2020; Zhu et al., 2021; Huang et al., 2021a). This property is defined as dynamic spatial correlation, i.e., the influence of the surroundings on the pollutant concentration at the predicted location varies over time. Therefore, the impact of dynamic spatial correlation must be incorporated into air pollutant concentrations prediction, especially to extract complex and non-linear spatial correlations in depth.

Dynamic temporal correlation Studies have shown that the concentration of air pollutants at a specific site changes dynamically and continuously in the temporal dimension (Zhang et al., 2016a, 2021a; Teng et al., 2022). This property is defined as dynamic temporal correlation, i.e., historical observation timesteps have different effects on prediction timesteps. Therefore, we must consider the impact of each timestep in the history on the prediction timestep, and the weight of the impact is dynamically updated, which needs to be calculated in real-time.

- Auxiliary factors

Air pollutant concentrations are also influenced by some other factors, like point of interests (POIs), which refer to the unique features of the target region. POIs features may include: factories, decoration and furniture markets, parks, subway stations, schools, etc. In addition to this, there are traffic, complex chemical mechanisms, meteorological conditions, regional geographic relationships, temporal features.

1.2. Related summaries on air pollutant concentration prediction

Some researchers have reviewed prediction approaches for air pollutant concentrations from different perspectives. Bai et al. reviewed the theory and application of statistical prediction methods, artificial intelligence methods, numerical prediction methods and hybrid models. In addition, based on a comparison of different prediction methods, the advantages and disadvantages of these models are also presented (Bai et al., 2018). Masih presented a survey of machine learning methods for air pollutant concentration prediction from 2013 to 2018. This work aims to focus on the fundamentals of machine learning techniques and their role in improving predictive performance. The following four main summaries were conducted: (1) the role of input predictors in improving the accuracy of model predictions; (2) geographic locations where these studies were conducted; (3) major machine learning techniques applied to pollution concentration prediction or estimation; (4) whether these techniques were based on Linear Regression (LR), Neural Network (NN), Support Vector Machine (SVM) or Ensemble learning algorithms (EL) (Masih, 2019). Cabaneros et al. mainly reviewed the use of Artificial Neural Networks (ANNs) for long-term prediction of outdoor $PM_{2.5}$, PM_{10}, oxides of nitrogen, and ozone. The vast majority of the identified works utilized meteorological and source emissions predictors almost exclusively. In conclusion, the results of the study demonstrate the need to formulate a systematic protocol for developing powerful ANNs models (Mclean Cabaneros et al., 2019). Liao et al. provided a brief review of recent attempts on using deep learning methods in air pollution prediction. Their main work is to introduce deep network architectures for air pollution prediction and their relevance to explore the non-linear spatio-temporal correlations across multiple scales of air pollution. The potential of deep learning techniques for air pollution prediction is then examined in terms of data gap filling, prediction algorithms, improvement of Chemical Transport Models (CTMs), satellite data estimation, and source estimation for atmospheric dispersion prediction (Liao et al., 2020). Masood and Ahmad presented an overview of artificial intelligence-based methods commonly used for air pollution prediction between 2003 and 2021. In addition, some technological gaps in these literatures and the pros and cons associated with the different AI techniques, were discussed (Masood and Ahmad, 2021). Despite the extensiveness of these reviews, they covered studies from a single or several aspects, and an overarching and comprehensive review for air pollutant concentration prediction is still on demand.

1.3. Classification of existing methods

Due to the progress of artificial intelligence, many algorithms have emerged to predict air pollutant concentrations. These approaches can be divided into two categories: non-deep learning methods and deep learning methods. The non-deep learning methods roughly include two major models: deterministic ones and statistical ones (Liu et al., 2021). The most representative deterministic methods are the Community Multiscale Air Quality (CMAQ) model (Mueller and Mallard, 2011; Thongthammachart et al., 2021; Kitagawa et al., 2021), the Weather Research and Forecasting model coupled with Chemistry (WRF-Chem) (Wang et al., 2022a; Zhou et al., 2017), Weather Research and Forecasting/Chemistry-Madrid (WRF/Chem-MADRID) (Chuang et al., 2011), the Nested Air Quality Prediction Modeling System (NAQPMS) (Wang et al., 2001, 2014), Chemical Lagrangian Model of the Stratosphere (CLaMS) (Konopka et al., 2010), Operational Street Pollution Models (OSPM) (Assael et al., 2008) and Comprehensive Air-quality Model with extension (CAMx) (Koo et al., 2015), LOTOS-EUROS (Manders et al., 2009), MOZART (Tie et al., 2006). Due to some reasons, such as the use of ideal theory in the determination of model structure and the estimation of parameters by experience, the predictive performance of these models is limited (Pak et al., 2020; Vautard et al., 2007; Stern et al., 2008). Statistical methods are well known to researchers because they avoid sophisticated theoretical models and simply apply statisticsbased models, gradually emerging in air pollution prediction (Ma et al., 2022a; Li et al., 2022a). These methods can also be classified into two categories, classical statistical ones and traditional machine learning ones. Classic statistical methods refer to those based on Auto Regression Integrated Moving Average (ARIMA) (Zhang et al., 2018; Balachandran et al., 2013; Ni et al., 2017; Nieto et al., 2018), or Geographically Weighted Regression (GWR) (Ma et al., 2014); while traditional machine learning methods usually use the Random Forest (RF) (Masmoudi et al., 2020), SVM (Nieto et al., 2018; Leong et al., 2020; Zhou et al., 2019; Li et al., 2018a; Li and Yang, 2010), LR (Beckerman et al., 2013; He et al., 2022) and ANNs (Kamal et al., 2006; Antanasijević et al., 2013; Wahid et al., 2011). These methods can capture non-linear features from raw data to a certain extent, but complex spatio-temporal correlations in the historical data cannot be fully extracted (Yan et al., 2021; Zhang et al., 2020a).

With the rapid growth of artificial intelligence and big data techniques, deep learning (DL) technologies have been extremely used in big data analysis to solve various classification and regression problems,

including: computer vision (Bengio et al., 2009), image classification (Chan et al., 2015), speech recognition (Mohamed et al., 2011), policy analysis (Strubell et al., 2020), time series prediction (Zhang et al., 2015) and natural language processing (Collobert and Weston, 2008), especially in the field of air pollution prediction (Zhao et al., 2020; Krishna Rani Samal et al., 2021a; Zhang et al., 2022a). They can not only predict specific values of pollutant concentrations, but also classify pollutant levels as well as achieve long-term prediction tasks for multiple days in the future (Krishna Rani Samal et al., 2021b; Macatangay and Hernandez, 2020). In addition to this, some researchers have shown that deep learning technologies determine the underlying reasons of meteorological conditions, seasonal variations, regional geographical relationships, chemical mechanisms, etc. that can change air pollutant concentrations (Zhang et al., 2021a; Kurt and Oktay, 2010; Bai et al., 2019a; Abdul-Wahab, 2001).

The advantages of deep learning technology in dealing with nonlinear spatio-temporal correlations have been gradually discovered, which has dramatically improved the accuracy of pollutants concentration prediction (Qi et al., 2019; Zhou et al., 2022). A typical deep learning method uses a hierarchical model to map the input to the final output (Goodfellow et al., 2016; Reichstein et al., 2019; LeCun et al., 2015; Bartlett et al., 2021). Its modeling idea is to construct certain blocks or layers together to form an end-to-end deep network structure. Deep learning models are quite suitable for processing historical air pollution data with spatio-temporal correlations. For instance, Convolutional Neural Networks (CNNs) (Rijal et al., 2018; Zhang et al., 2016b; Bo et al., 2018; Chakma et al., 2017) are used to extract spatial correlation in regional multi-site data; Graph Convolutional Neural Networks (GCNs) (Qi et al., 2019; Bruna et al., 2013) apply convolution operations to graph structure data, thus they can well represent the network of air quality monitoring sites in non-Euclidean space. Recurrent Neural Networks (RNNs), like the Original Recurrent Neural Network (Original RNN) (Elman, 1991; Athira et al., 2018; Singh et al., 2012; Loy-Benitez et al., 2019) and its variants, Gated Recurrent Units (GRUs) (Loy-Benitez et al., 2019; Cho et al., 2014; Huang et al., 2021b; Xu et al., 2021), Long Short-Term Memory (LSTM) (Loy-Benitez et al., 2019; Hochreiter and Schmidhuber, 1997; Lu et al., 2021a; Ulpiani et al., 2022; Zhao et al., 2019; Navares and Aznarte, 2020; Wu et al., 2022), Read-first LSTM (RLSTM) (Zhang et al., 2021a), Long Short-Term Memory Neural Network Extended (LSTME) (Li et al., 2017), can be used to extract temporal correlation in raw data. Convolutional Neural Network- Long Short-Term Memory (CNN-LSTM) based on CNN and LSTM (Pak et al., 2018, 2020; Zhu et al., 2021; Yan et al., 2021; Mengara et al., 2020; Soh et al., 2018; Wen et al., 2019) can be used to extract spatio-temporal correlations from historical data. Here we summarize the key techniques commonly used in existing air pollutant concentration prediction methods, as shown in Fig. 1. The full names of the abbreviated methods mentioned in the paper are listed in Table 1, Table 2 and Table 3, where Table 1 corresponds to deterministic methods, Table 2 to statistical methods and Table 3 to deep learning methods.

1.4. Literature search and select strategy

The literature search focused on the highly indexed database Google Scholar and Web of Science journal publications to systematically study the relevant literature published in the last decade. They are one of the few compiling the most important scientific databases such as: IEEE

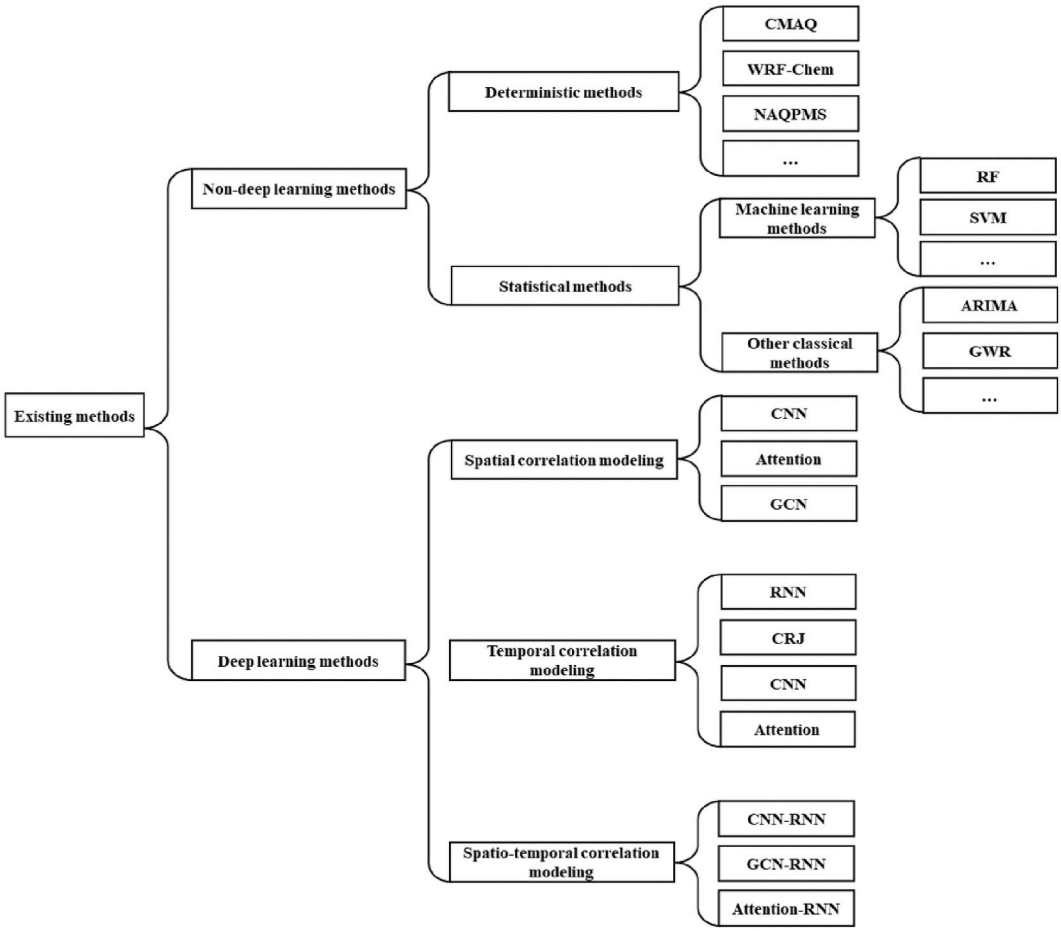

Fig. 1. Classification of existing methods for air pollutant concentration prediction.

Table 1
The description of deterministic methods.

Model name	Full name
CAMx (Koo et al., 2015)	Comprehensive Air-quality Model with extension
CMAQ (Mueller and Mallard, 2011; Thongthammachart et al., 2021; Kitagawa et al., 2021)	Community Multiscale Air Quality
CLaMS (Konopka et al., 2010)	Chemical Lagrangian Model of the Stratosphere
CTMs (Zhu et al., 2017)	Chemical Transport Models
NAQPMS (Wang et al., 2001, 2014)	Nested Air Quality Prediction Modeling System
OSPM (Assael et al., 2008)	Operational Street Pollution Models
WRF (Thongthammachart et al., 2021; Wang et al., 2022a; Zhou et al., 2017; Chuang et al., 2011)	Weather Research and Forecasting
WRF-Chem (Wang et al., 2022a; Zhou et al., 2017)	Weather Research and Forecasting/Chemistry
WRF/Chem-MADRID (Chuang et al., 2011)	Weather Research and Forecasting/Chemistry-Madrid

Table 2
The description of statistical methods.

Model name	Full name
ARIMA (Zhang et al., 2018; Balachandran et al., 2013; Ni et al., 2017; Nieto et al., 2018)	Autoregressive Integrated Moving Average Model
ANNs (Kamal et al., 2006; Antanasijević et al., 2013; Wahid et al., 2011)	Artificial Neural Networks
BPNN (Kamal et al., 2006)	Backpropagation Neural Network
DWT (Cabaneros et al., 2020)	Discrete Wavelet Transform
EMD (Huang et al., 1998)	Empirical Mode Decomposition
GWR (Ma et al., 2014)	Geographically Weighted Regression
GRNN (Antanasijević et al., 2013)	Generalized Regression Neural Network
LR (Beckerman et al., 2013; He et al., 2022)	Linear Regression
LSSVM (Li and Yang, 2010)	Least Squares Support Vector Machine
RF (Masmoudi et al., 2020)	Random Forest
RBFNN (Wahid et al., 2011)	Radial Basis Function Neural Network
SVM (Nieto et al., 2018; Leong et al., 2020; Zhou et al., 2019; Li et al., 2018a; Li and Yang, 2010)	Support Vector Machine
WT (Cabaneros et al., 2020; Zeng et al., 2022; Daubechies, 1992; Cheng et al., 2021)	Wavelet Transform

Xplore, ScienceDirect and Springer, where major papers on air pollutant concentration prediction can be found. The search terms include different combinations of "air pollutant concentration", "air quality", "prediction", "deep learning", "machine learning", "forecast", "hybrid model". The main objective is to analyze the most authoritative scientific research papers in related fields worldwide in recent years. In addition, a number of quality conference papers were selected for joint study. The search process was repeated until the relevant citation stopped. Afterwards, a total of 226 papers were screened through the literature search. The literature was classified according to the input variables, modeling process, and prediction task type. Besides the citations of original methodology papers, the application papers were published in 2000–2022, with 90 percent of them published in 2015–2022.

Further selection was based on the impact factor of these papers and the Journal Citation Reports (JCR) partition. The limation of 27 papers were to focus on the recent quartiles of the journals, according to JCR, which conclude the Q1-Q4 categories. Therefore, it is not for reference because of low impact factors. Finally, excluding the 41 papers on basic methods and principles introduction, a total of 158 application papers were included in the reference.

Table 3
The description of deep learning methods.

Model name	Full name
Attention-LSTM (Zhu et al., 2021; Huang et al., 2021a; Gao and Li, 2021)	Spatial Attention Mechanism-Long Short-Term Memory
Attention (Zhu et al., 2021; Huang et al., 2021a; Gao and Li, 2021)	Spatial Attention Mechanism
Attention (Wang et al., 2020; Jia et al., 2021; Tu et al., 2021; Bahdanau et al., 2014)	Attention Mechanism
BiLSTM (Zhang et al., 2021a)	Bidirectional Long Short-Term Memory Network
CRJ (Sheta et al., 2018; Mo et al., 2020)	Cycle Reservoir with Regular Jumps
CNNs (Rijal et al., 2018; Zhang et al., 2016b; Bo et al., 2018; Chakma et al., 2017; Sayeed et al., 2020)	Convolutional Neural Networks
CNN-LSTM [8, 9, 52, 93–96]	Convolutional Neural Network- Long Short-Term Memory
C-LSTME (Wen et al., 2019)	Convolutional and Long Short-Term Memory Neural Network Extended
CNN-GRU (Zhang et al., 2020b)	Convolutional Neural Network- Gated Recurrent Unit
EEMD-LSTM (Bai et al., 2019b)	Ensemble Empirical Mode Decomposition- Long Short-Term Memory
ESNs (Jaeger and Haas, 2004; Zhang et al., 2021b; Li and Tanaka, 2022)	Echo State Networks
EMD-GRU (Huang et al., 2021b)	Empirical Mode Decomposition-Gated Recurrent Unit
EDS Model (Zhang et al., 2021a)	Encoder-Decoder Stacked Model based on Read-first LSTM
FNNs (Schmidhuber, 2015)	Feedforward Neural Networks
GRUs (Loy-Benitez et al., 2019; Cho et al., 2014; Huang et al., 2021b; Xu et al., 2021)	Gated Recurrent Units
GCNs (Bruna et al., 2013)	Graph Convolutional Neural Networks
GCN-LSTM (Qi et al., 2019)	Graph Convolutional Neural Network-Long Short-Term Memory
LSTM (Loy-Benitez et al., 2019; Hochreiter and Schmidhuber, 1997; Lu et al., 2021a; Ulpiani et al., 2022; Zhao et al., 2019; Navares and Aznarte, 2020; Wu et al., 2022)	Long Short-Term Memory
LSTME (Li et al., 2017)	Long Short-Term Memory Neural Network Extended
Lag-LSTM (Ma et al., 2020a)	Lag Layer-Long Short-Term Memory
MTCAN (Krishna Rani Samal et al., 2021b)	Multi-directional Temporal Convolutional Artificial Neural Network
Original RNN (Elman, 1991; Athira et al., 2018; Singh et al., 2012; Loy-Benitez et al., 2019)	Original Recurrent Neural Network
RNNs (Zhang et al., 2021a; Athira et al., 2018; Singh et al., 2012; Loy-Benitez et al., 2019; Huang et al., 2021b; Xu et al., 2021; Lu et al., 2021a; Ulpiani et al., 2022; Zhao et al., 2019; Navares and Aznarte, 2020; Wu et al., 2022; Li et al., 2017)	Recurrent Neural Networks
RLSTM (Zhang et al., 2021a)	Read-first LSTM
Seq2Seq (Wang et al., 2020; Jia et al., 2021; Tu et al., 2021)	Sequence to Sequence
SA-LSTM (Shi et al., 2021)	Spatial Attention-based Long Short-Term Memory
TLS-BLSTM (Ma et al., 2020b)	Transfer Stacked Bidirectional Long Short-Term Memory Network
TCN (Krishna Rani Samal et al., 2021b, 2021c, 2021d; Jiang et al., 2021; Zhang et al., 2021c)	Temporal Convolutional Network

1.5. Our contributions

We intend to present an overview of recent approaches for air pollutant concentration prediction that utilize deep learning technologies. To our knowledge, it is the comprehensive analysis on this scope

from multiple perspectives, including methods, public datasets, experiment analysis, current challenges and future directions. The contributions of this review are as follows:

- We categorize the existing methods and conduct a comprehensive review on current deep learning methods for air pollutant concentration prediction. We specifically analyze their characteristics and principles from the perspectives of temporal, spatial and spatio-temporal relations.
- We focus on some advanced techniques, including data decomposition, transfer learning and statistical methods, that are fused into deep learning models for air pollutant concentration prediction. This demonstrates the feasibility of these techniques to help improve the prediction performance on certain air pollution prediction tasks.
- We list major public datasets and commonly used auxiliary features for air pollutant concentration prediction. This would provide a good reference for subsequent research, and can help researchers in this field to better identify the foothold.
- We compare the results of experiments conducted by deep learning and non-deep learning models on these listed datasets, and some valuable conclusions were drawn based on the comparison.
- We outline the existing challenges and limitations of the deep learning methods for air pollutant concentration prediction and suggest some future development directions of this field.

The rest of the paper is organized as follows: Section 2 summarizes non-deep learning methods for air pollutant concentration prediction from the perspective of characteristic, application and limitation. Section 3 reviews deep learning methods for air pollutant concentration prediction, including commonly used techniques for modeling temporal and spatial correlations and some other new variants. Section 4 lists major public datasets and important auxiliary features for air pollutant concentration prediction. Section 5 generalizes representative experiments of the deep learning and non-deep learning models for different prediction tasks on the listed public datasets and draws some conclusions. Section 6 identifies existing limitations and the future research directions of this field. Some conclusions are drawn in Section 7.

2. Air pollutant concentration prediction based ON NON-DEEP learning

Non-deep learning methods for air pollutant concentration prediction extend in two directions: deterministic methods and statistical methods. Table 4 lists current most representative ones.

Deterministic methods, adopt meteorological principles and mathematical equations to simulate the process of pollutant emission, transformation, diffusion and removal based on atmospheric physical and chemical reactions (Li et al., 2017). For example, CTMs are designed to describe chemical and meteorological processes in the atmosphere, focusing on the emission, transport and transformation of air pollutants to establish mathematical algorithms (Zhu et al., 2017). The Weather Research and Forecasting (WRF) models (Thongthammachart et al., 2021) are used for atmospheric research and application in prediction, such as WRF-Chem (Wang et al., 2022a; Zhou et al., 2017) and WRF/Chem-MADRID (Chuang et al., 2011). In addition, other deterministic methods such as CMAQ (Mueller and Mallard, 2011; Thongthammachart et al., 2021; Kitagawa et al., 2021), CAMx (Koo et al., 2015) are also applied to air pollution prediction (Liu et al., 2021). Chemical dynamic conditions, reaction index, and chemical products need to be included in the reference range. Although developed theories provide valuable insights for understanding air pollution prediction, these deterministic models are associated with complex priori knowledges, unreliable and limited data, and various usage limitations. It is not enough to explain the nonlinearity of many factors related to the formation of pollutants (Pak et al., 2020; Vautard et al., 2007; Stern et al., 2008). To circumvent these deficiencies, some researchers have started to apply statistical methods to cope with them.

Table 4
Classification of non-deep learning methods for air pollutant concentration prediction.

Category		Representative models	Literatures
Deterministic methods		**CMAQ**	(Mueller and Mallard, 2011; Thongthammachart et al., 2021; Kitagawa et al., 2021)
		WRF	(Thongthammachart et al., 2021; Wang et al., 2022a; Zhou et al., 2017; Chuang et al., 2011)
		NAQPMS	(Wang et al., 2001, 2014)
		MOZART	Tie et al. (2006)
		CLaMS	Konopka et al. (2010)
		LOTOS-EUROS	Manders et al. (2009)
		OSPM	Assael et al. (2008)
		CAMx	Koo et al. (2015)
Statistical methods	machine learning	**LR**	(Beckerman et al., 2013; He et al., 2022)
		ANNs	(Kamal et al., 2006; Antanasijević et al., 2013; Wahid et al., 2011)
		RF	Masmoudi et al. (2020)
		SVM	(Nieto et al., 2018; Leong et al., 2020; Zhou et al., 2019; Li et al., 2018a; Li and Yang, 2010)
	Classic statistical	**ARIMA**	(Zhang et al., 2018; Balachandran et al., 2013; Ni et al., 2017; Nieto et al., 2018)
		GWR	Ma et al. (2014)

Unlike the deterministic models, statistical methods unravel non-linear relationships between various variables that may affect air pollutant concentrations (Zhang et al., 2018; Balachandran et al., 2013; Ni et al., 2017; Nieto et al., 2018; Ma et al., 2014). They usually deploy mathematical theories including statistics, probability, and stochastic processes, and can be divided into two categories, classical methods and traditional machine learning methods. A typical classical method is ARIMA (Zhang et al., 2018; Balachandran et al., 2013; Ni et al., 2017; Nieto et al., 2018). ARIMA is a traditional time series prediction method which integrates moving average and autoregressive components to model historical time sequence data. Ni et al. used an experiment in Beijing to demonstrate that the ARIMA model can predict $PM_{2.5}$ concentration more accurately for a short-term of 1 h (Ni et al., 2017). However, these methods involve considerable amounts of statistical data, and rely on certain empirical rules to make predictions. And they cannot fully capture non-linear correlations in air pollutant concentration data. Therefore, some researchers have applied traditional machine learning methods for better solutions.

The main advantage of the traditional machine learning methods over the classical statistical methods is its ability to handle non-linear features, resulting in higher prediction accuracy (Zhang et al., 2012). In addition, the application does not require a deep understanding of the dynamic and chemical processes between air pollutants and other relative variables in the atmosphere (Mclean Cabaneros et al., 2019). A common machine learning predictor is ANNs, which simulates the system of the human brain and nervous to model non-linear sequence. ANNs have also improved in years of research and applications, bringing more evolved versions to air pollution prediction, including the Back-propagation Neural Network (BPNN) (Kamal et al., 2006), the Generalized Regression Neural Network (GRNN) (Antanasijević et al., 2013), the Radial Basis Function Neural Network (RBFNN) (Wahid et al., 2011). Other models, like SVM, have also received a lot of attention in air pollution prediction. Similar to ANNs, there are improved versions of SVMs that can improve the prediction performance over the original model, such as the Least Squares Support Vector Machine (LSSVM) (Li and Yang, 2010).

Although statistical methods have elevated the prediction accuracy from previous models, they are adapt to learn shallow hidden features and hold limited ability of extracting complex and non-linear spatio-temporal correlations and they only work well on small-scale datasets (Yan et al., 2021; Zhang et al., 2020a). Therefore, it is not enough for complex and dynamic air pollutant concentration data on a large scale and with complex spatio-temporal correlations.

3. Air pollutant concentration prediction based on deep learning

The deep learning network architectures determine their ability to extract complex and non-linear spatio-temporal correlations from data. Unlike shallow ANNs, the deep learning networks have multiple layers of neurons, which are called deep network structures. The deep network structures formed by the connection of these neurons and the settings of the activation function in the networks make them suitable for various application fields. The deep learning models have powerful capabilities in the extraction of spatio-temporal correlations, so they are suitable for air pollutant concentration prediction.

According to their ability to extract temporal and spatial correlations, we briefly introduce some commonly used deep learning models. The models adapting to temporal correlation predictions include LSTM, GRU, Temporal Convolutional Network (TCN). The models applied to spatially correlated feature extraction include CNN, GCN, Spatial Attention Mechanism (Attention). Spatio-temporal Deep Learning Architectures (STDL) can be built by coupling temporal and spatial modules. The STDL architectures support dealing with air pollution-related data due to their ability to represent complex and non-linear spatio-temporal correlations. Different architectures of deep networks applied to air pollutant concentration prediction are shown in Fig. 2.

Table 5 presents the classification of current deep learning-based methods from the perspectives of spatial and temporal correlations the models can extract. Detailed explanation on their respect theories and applications are extended as follows.

Table 5
Classification of Deep learning methods for air pollutant concentration prediction.

Spatial modeling	Temporal modeling		Literatures
CNN	\		(Rijal et al., 2018; Zhang et al., 2016b; Bo et al., 2018; Chakma et al., 2017)
CNN	**LSTM**		(Pak et al., 2018, 2020; Zhu et al., 2021; Yan et al., 2021; Mengara et al., 2020; Soh et al., 2018; Wen et al., 2019)
	GRU		Zhang et al. (2020b)
	LSTM + Attention		Zhang et al. (2022b)
GCN	**LSTM**		Qi et al. (2019)
Attention	**LSTM**		(Zhu et al., 2021; Huang et al., 2021a; Gao and Li, 2021)
\	**CNN**	\	Sayeed et al. (2020)
		Dilated Causal Convolution	(Krishna Rani Samal et al., 2021b, 2021c, 2021d; Jiang et al., 2021; Zhang et al., 2021c)
\	**Original RNN**	**+Auto-encoder**	Ong et al. (2016)
		\	(Athira et al., 2018; Singh et al., 2012; Loy-Benitez et al., 2019)
\	**GRU**	**Seq2seq with GRU(+Attention)**	(Wang et al., 2020; Jia et al., 2021)
		\	(Loy-Benitez et al., 2019; Huang et al., 2021b; Xu et al., 2021)
\	**LSTM**	\	(Zhang et al., 2021a; Loy-Benitez et al., 2019; Lu et al., 2021a; Ulpiani et al., 2022; Zhao et al., 2019; Navares and Aznarte, 2020; Wu et al., 2022; Li et al., 2017)
		+Auto-encoder	(Zhang et al., 2020a; Saravanan and Kumar, 2021)
		Seq2seq with LSTM (+Attention)	(Wang et al., 2020; Tu et al., 2021)
\	**CRJ**		(Sheta et al., 2018; Mo et al., 2020)

3.1. Modeling spatial correlation

CNNs Many scholars have deployed CNNs to capture the spatial correlation in the data of air pollutant concentrations (Pak et al., 2018, 2020; Zhu et al., 2021; Yan et al., 2021; Rijal et al., 2018; Zhang et al., 2016b, 2020b, 2022b; Bo et al., 2018; Chakma et al., 2017; Mengara et al., 2020; Soh et al., 2018; Wen et al., 2019). CNN (LeCun et al., 1998) is a deep feedforward network composed of convolutional layers. They are capable of analyzing multiscale shift invariant features of data. A subsampling operation is performed between two consecutive convolutional layers. Two commonly used subsampling operations are max pooling and mean pooling. Pooling layers can be replaced by convolutional layers, simplifying the network structure (Springenberg et al., 2014). The units in the convolution layer are organized in the feature map, and each unit is connected to the local weights in the feature map of the previous layer through filters. The sum of the local weights is passed through an activation function that can take various forms, such as a Rectified Linear Units (ReLU) (Şahin et al., 2011). Some researchers integrated spatial data between different regions to a one-dimensional

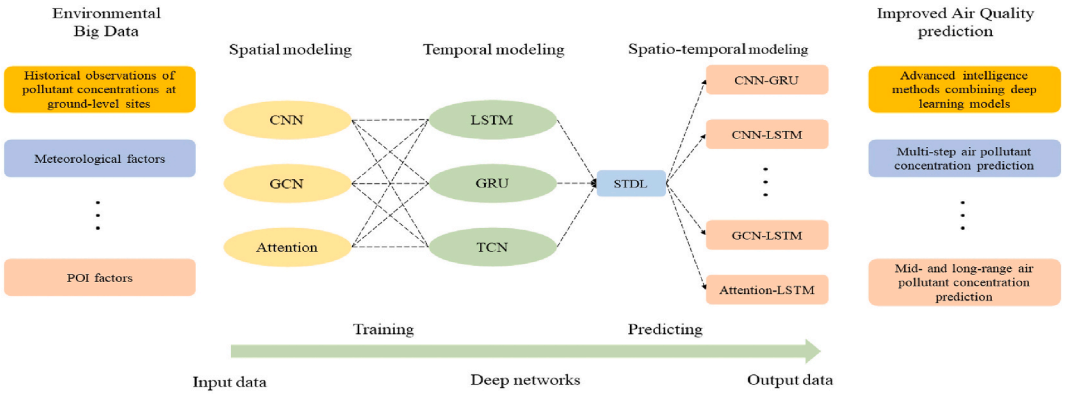

Fig. 2. Air pollutant concentration prediction framework based on deep learning.

or two-dimensional tensor, thus the CNN was facilitated to extract the spatial correlation hidden in the tensor (Yan et al., 2021; Mengara et al., 2020). However, the distributions of regions are not uniform, and encapsulating them into a one-dimensional or two-dimensional tensor destroys the original spatial correlation. Therefore, several studies attempted to convert these spatial data into standard grids. Each of them represents a region and the center one is the region to be predicted. For example, Soh et al. designed a matrix of 121 square sections where the center grid represents the observed location and others the regions surrounding it. In this study, CNN can extract useful spatial correlation information from the grids (Soh et al., 2018). Some other researchers noticed CNNs great achievements in computer vision and utilized this expertise to extract spatial relations in images. Rijal et al. took images of the predicted area as the input and developed three CNN models with different structures to extract spatial correlation for $PM_{2.5}$ concentration assessment (Rijal et al., 2018). Zhang et al. also regarded images as the target for pollution prediction and applied a CNN model containing nine convolution layers, two pooling layers and two dropout layers. The convolutional layers are used to extract the spatial correlation in the raw images, and the dropout layers are used to prevent overfitting (Zhang et al., 2016b).

GCNs CNNs are born to operate on Euclidean spaces. Since spatial data among multiple regions usually form a non-Euclidean structure, some researchers steer to GCNs for air pollutant concentration prediction (Qi et al., 2019). In this application, GCNs are usually based on the spectral method. They define the spectral graph convolution based on the graph Fourier Transform and the Laplacian matrix L. $x \in \mathbb{R}^N$ is set as a signal on the nodes of the undirected graph G where x_i represents a scalar signal on the i-th node. The expression of the spectral graph convolution is the multiplication of the convolution kernel g_θ and the signal x in the Fourier domain. The spectral graph convolution operator $*$ is defined as

$$y = g_\theta * x = g_\theta(L)x = g_\theta\left(U\Lambda U^T\right)x = Ug_\theta(\Lambda)U^T x \tag{1}$$

Where $\theta \in \mathbb{R}^N$ is the Fourier coefficient that needs to be trained. $L \in \mathbb{R}^{N\times N}$ is the normalized graph Laplacian, and described as

$$L = I_N - D^{-\frac{1}{2}}AD^{-\frac{1}{2}} = U\Lambda U^T \tag{2}$$

Where $I_N \in \mathbb{R}^{N\times N}$ is the identity matrix. $D \in \mathbb{R}^{N\times N}$ is the diagonal matrix, $D_{ii} = \sum_j A_{i,j}$ (Chung and Graham, 1997). $\Lambda \in \mathbb{R}^{N\times N}$ is the diagonal matrix of eigenvalues of L. $U \in \mathbb{R}^{N\times N}$ is the matrix of eigenvectors of L. Convolution kernel g_θ can be interpreted as a function of the eigenvalues of L, i.e. $g_\theta(\Lambda)$. $U^T x$ represents the Graph Fourier Transform of x.

Calculating spectral graph convolution costs too much due to $\mathcal{O}(n^2)$ multiplications with matrix U. In practice, the truncated expansion of $g_\theta(\Lambda)$ by Chebyshev polynomials is used to reduce the computational cost (Defferrard et al., 2016). Equation (1) can be generalized by Chebyshev polynomials as:

$$H = \sum_{k=0}^{K} T_k(\widetilde{L})X_t\Theta_k \tag{3}$$

Where $X_t \in \mathbb{R}^{N\times M}$ is the signal matrix. $\Theta_k \in \mathbb{R}^{M\times W}$ is the matrix of convolution kernel parameters. $H \in \mathbb{R}^{N\times W}$ is the convolved spatial feature matrix. $T_k(\widetilde{L}) \in \mathbb{R}^{N\times N}$ is the Chebyshev polynomial of the order k. The scaled Laplacian $\widetilde{L} = \frac{2L}{\lambda_{\max}} - I_N$. $\lambda_{\max}$ represents the largest eigenvalue of L. For the input variable s, T_k is defined as $T_k(s) = 2sT_{k-1}(s) - T_{k-2}(s)$, which is a recurrence relation when $T_0 = 1$ and $T_1 = s$.

GCNs can be an effective tool to mine the spatial information among different regions for air pollution prediction. Qi et al. presented a good example. They modeled spatial data as an undirected graph rather than in the way of modeling Euclidean data. In a graph, nodes represent the monitor sites and edges the connections between two sites. The spatial weight matrix is constructed based on distances between sites, which is reasonable given the quantitative spatial correlation among sites. The graph is fed into a GCN based on the spectral method to extract features in the spatial domain and Chebyshev polynomials are also introduced to simplify calculations (Qi et al., 2019).

Attention The Attention Mechanism is first applied to the field of Natural Language Processing (NLP) (Bahdanau et al., 2014). Air pollutant concentrations recorded by one site monitor can be affected by its surrounding sites. The Spatial Attention Mechanism is used to capture the spatial correlation between sites in air pollutant concentration prediction (Zhu et al., 2021; Huang et al., 2021a; Gao and Li, 2021). Its core theory is to assign different weights according to the spatial correlation degrees of different sites. Suppose a node in a graph represents a site. Given a set of node features $\widehat{X}_t = \{\widehat{x}_1, \widehat{x}_2, \ldots, \widehat{x}_N\}, \widehat{x}_i \in R^M$, where N represents the number of nodes, and M represents the number of features of each node. The spatial correlation index between different sites can be expressed as

$$e_{i,j} = \sigma\left(W_\beta^T\left[W\widehat{x}_i, W\widehat{x}_j\right]\right) \tag{4}$$

where W represents the input feature weight matrix of the node. W_β represents the weight parameter vector of the fully connected layer. $e_{i,j}$ represents the spatial correlation strength of the feature of node j on node i. σ is the activation function.

The weight coefficient $\gamma_{i,j}$ of node j relative to node i can be calculated as:

$$\gamma_{i,j} = \frac{\exp(e_{ij})}{\sum_{k=1}^{n}\exp(e_{ik})} \tag{5}$$

where $\gamma_{i,j}$ denotes the importance of node j to node i.

Huang et al. implemented a representative application using the Spatial Attention Mechanism. They introduced an improved version of the graph-based Spatial Attention Mechanism to leverage a self-loop normalized adjacency matrix and extract the spatial correlation between different sites (Huang et al., 2021a).

3.2. Modeling temporal correlation

CNNs Gehring et al. applied fully convolutional neural networks for feature extraction and verified the feasibility of CNNs to process sequence structure data (Gehring et al., 2017). Some researchers appropriated this ability for air pollutant concentration prediction. For example, Sayeed et al. used a five-layer deep convolutional neural network to extract the temporal correlation from historical observation data and predict the ozone concentration in the next 24 h (Sayeed et al., 2020).

Dilated Causal Convolution is another choice to deal temporal data. It is a special standard 1D-convolution that regulates the size of the receptive field by changing the value of the dilation rate. It is particularly suitable to capture long-term temporal correlation. Some studies (Krishna Rani Samal et al., 2021b, 2021c, 2021d; Jiang et al., 2021; Zhang et al., 2021c) used it as a time convolution layer to extract the temporal correlation of air pollutants. Compared with recurrent networks, convolutional networks have a fixed-size context representation. Expanding the depth of the network by stacking layers can make the size of the effective context larger. Calculations over all the elements in the sequence can be exerted in parallel, which can fully harness GPU resources and is easier to optimize. This is superior to RNNs that, maintain the entire hidden state in the past timesteps.

RNNs Original RNNs, are variants of Feedforward Neural Networks (FNNs) (Schmidhuber, 2015). FNNs enable signals to travel only one way from input to output. They are straightforward network structures without recurrent connections associated with inputs and outputs (Baby and Alexander, 2018). On the basis of FNNs, Original RNNs introduces the self-connection of neuronal circulatory structure into the network (Elman, 1991). Thus, the key information of the input data can be

memorized. The sequence of data can have a certain impact on the output of the network. LSTM are enhanced versions of the Original RNNs (Hochreiter and Schmidhuber, 1997). They introduce memory blocks to overcome vanishing and exploding gradients. The memory block consists of three gated units: the input gate, output gate, and forget gate. The multiplicative gates control the memory block operation and determine whether the input information need to be remembered. The input gate controls the flow of cell activation from input into a memory cell, while output gate controls the flow of output from a memory cell into other nodes (LeCun et al., 2015). Compared with Original RNNs, LSTM networks can better handle long time sequences data. The GRUs are simplification of the LSTM models (Cho et al., 2014). They are simple structure consisting of only update gates and reset gates (LeCun et al., 2015). The update gate replaces the input gate and forget gate in LSTM, and its function is to decide whether the information needs to be remembered. Compared with LSTM, the advantage of using GRUs is that they are more lightweight, requires fewer parameters to be trained, and the training speed is faster. And in some research tasks, GRUs show the same excellent performance as LSTM (Chung et al., 2014). RNNs (including the original RNNs and their variants with GRUs and LSTM), have been widely used to process sequential data. To model the complex and non-linear temporal correlation of historical pollutant data, RNNs were deployed to deal various air pollutant concentration prediction tasks (Zhang et al., 2021a; Athira et al., 2018; Singh et al., 2012; Loy--Benitez et al., 2019; Huang et al., 2021b; Xu et al., 2021; Lu et al., 2021a; Ulpiani et al., 2022; Zhao et al., 2019; Navares and Aznarte, 2020; Wu et al., 2022; Li et al., 2017). However, given the way that RNNs processes data in the order of sequence data, when modeling long time sequence, these models are inept at remembering information they have learned many time-steps before (Hochreiter and Schmidhuber, 1997; Hochreiter et al., 2001).

In the RNN-based air pollutant concentration prediction, a network structure called encoder-decoder is also used by some researchers (Zhang et al., 2020a; Wang et al., 2020; Jia et al., 2021; Tu et al., 2021; Ong et al., 2016; Saravanan and Kumar, 2021). It is to encode historical observation data into a fixed-length vector and then decode the final prediction from the information in the vector. The encoder-decoder network is described as:

$$h = \omega(\rho_t; \beta_1) \tag{6}$$

$$X_{t+1:t+s} = f(h; \beta_2) \tag{7}$$

where ω is the encoder and f is the decoder; ρ_t represents the input information at timestep t; h is represented by the semantic vector output by the encoder; $X_{t+1:t+s}$ is s-timestep-ahead prediction values; β_1 and β_2 are trained parameters.

The encoder-decoder network structure can also ignore important temporal information. Because however long the input and the output sequences are, the length of the semantic vector between the encoder and the decoder is always fixed. If the input sequence is too long, some important information may be lost.

Attention To avoid losing temporal information, researchers have added the Attention Mechanism to the encoderdecoder network. The Attention Mechanism can adaptively select important hidden state information as the input of the decoder, and discard redundant one. The selection is fulfilled by assigning different weights on different hidden states of the historical data. The Attention Mechanism can model the non-linear temporal correlation between the observed data, even if the input is too long.

Some studies on air pollutant prediction that utilize the Attention Mechanism have achieved satisfying results. Wang et al. integrated an Attention Mechanism into a sequence to sequence (seq2seq) model to extract the temporal correlation in the hidden state at different past timesteps (Wang et al., 2020). Tu et al. proposed an improved Attention Mechanism that integrates time decay factor into the traditional Attention Mechanism. The time decay factor can alleviate the impact of the value observed from a longer time before while increasing the impact of the value from a closer time point. Their structure also incorporated the hidden states in the decoder to push the prediction spreading forward and thus to achieve long-term prediction for air pollutant concentration (Tu et al., 2021).

CRJ Cycle Reservoir with Regular Jumps (CRJ) is the improved version of the Echo State Networks (ESNs) (Jaeger and Haas, 2004). In ESNs, only the output layer weights are trained and all the input and reservoir layers weights are randomly initialized and scaled with a scaling parameter. ESNs have been applied to time series modeling (Zhang et al., 2021b; Li and Tanaka, 2022). However, the random connectivity and weight structure of ESNs limit their performance. In regard of this, the CRJ network was proposed by Rodan and Tiňo (Ali and Peter, 2012). A CRJ network is composed of input layers, hidden layers and output layers. A hidden layer has a fixed regular topology: Nodes in the hidden layer are connected in an un-directional cycle with bi-directional shortcuts (jumps).

The CRJ network can exploit the sequence information by extracting temporal correlation and predict air pollutant concentrations. In (Sheta et al., 2018), the CRJ network was used to predict the ground-level ozone pollution of two sites. In (Mo et al., 2020), CRJ was not directly used for prediction but to extract temporal correlation from historical data of ozone concentrations.

3.3. Deep learning modeling of joint spatio-temporal correlations

Although many methods utilize the learning ability of deep learning techniques to extract temporal or spatial correlation from air pollution data, they treat the temporal correlation and the spatial correlation separately and ignore possible connections between them. Some researchers have applied hybrid methods that consider the relations between the two types of correlation, as listed in Table 5, and obtain higher prediction accuracy. These hybrid methods consist of three modules: a spatial module, a deduction module, and a temporal prediction module. The spatial module, usually based on CNNs or GCNs, etc., extracts spatial correlation that will be sent into the temporal module, usually based on RNNs or CRJ, etc. The deduction module serves as the bridge between the spatial module and the temporal module and calculates the causal relationship between the spatial and the temporal through a matrix multiplication or other types of operations. For example, Pak et al. used a spatio-temporal model (CNN-LSTM) to predict the average $PM_{2.5}$ concentration of Beijing in the next day. They introduced the mutual information (MI) estimator to analyze the temporal and spatial correlations and constructed the spatio-temporal feature vector to reflect the non-linear spatio-temporal correlations. Then, they deployed a CNN to extract important spatial correlation and LSTM to process the temporal correlation. The outputs of the two modules were regard as spatio-temporal correlations for final prediction (Pak et al., 2020). Another similar hybrid deep learning model is for the non-Euclidean structure data. Qi et al. developed a model of Graph Convolutional Neural Network- Long Short-Term Memory (GCN-LSTM) to predict air pollutant concentration and obtained better results, compared to CNN-LSTM model (Qi et al., 2019).

3.4. Deep learning plus other technologies

Deep learning approaches have outperformed non-deep learning methods in pollutant concentration prediction tasks and received a lot of attention, but is still in a developmental stage, and prediction accuracy is constantly improving. Since the deep learning approaches are constrained by their structure and training data, e.g., the problem of handling non-stationarity data (Huang et al., 2021b; Cabaneros et al., 2020; Zeng et al., 2022; Cheng et al., 2021; Bai et al., 2019b; Jiang et al., 2021; Wang et al., 2022b), data shortage (Ma et al., 2019, 2020b; Fong et al., 2020) and model structure constraints (Xu et al., 2021; Ma et al.,

2020a; Kim et al., 2021; Gu et al., 2022; Chen et al., 2021a; Han et al., 2022), it is not easy to fully reflect the advantages in the task of pollutant concentration prediction. Currently, many studies have improved methods based on deep learning, including improvements in input data, model structure and multi-type model mixing. For example, many researchers have integrated other technologies into the deep learning methods for air pollutant concentration prediction (Huang et al., 2021b; Xu et al., 2021; Cabaneros et al., 2020; Zeng et al., 2022; Cheng et al., 2021; Bai et al., 2019b; Ma et al., 2019, 2020a, 2020b; Jiang et al., 2021; Wang et al., 2022b; Fong et al., 2020; Kim et al., 2021; Gu et al., 2022; Chen et al., 2021a; Han et al., 2022) to fix these flaws.

Combining non-linear temporal correlation in historical pollutants concentration series, more and more deep learning methods are currently being applied to air pollution prediction. But most of them ignore the non-stationarity of time series, which leads to a lower accuracy of prediction (Huang et al., 2021b). A typical choice is to incorporate the data decomposition technology into the deep learning methods, as shown in Fig. 3. It works in this way: the data decomposition module (e.g. Wavelet Transform (WT), Empirical Mode Decomposition (EMD) or their variants (Huang et al., 1998; Daubechies, 1992)) decomposes the original time series into several sub-sequences and each sub-sequence is fed into its corresponding deep learning model to output its predicted result. Then all the predicted results of the sub-sequences are aggregated for obtaining the final prediction. Some studies have adopted this method and achieved excellent performance in air pollutant concentration prediction (Huang et al., 2021b; Cabaneros et al., 2020; Zeng et al., 2022; Cheng et al., 2021; Bai et al., 2019b; Jiang et al., 2021; Wang et al., 2022b). For example, Cabaneros et al. utilized a new hybrid method based on LSTM and the Discrete Wavelet Transform (DWT), and applied it to NO_2 prediction at six urban locations in Central London in the next hour (Cabaneros et al., 2020). Bai et al. took advantage of an Ensemble Empirical Mode Decomposition-Long Short-Term Memory (EEMD-LSTM) model for $PM_{2.5}$ concentration prediction. In this model, EEMD decomposes the original target pollutant data, and a single predictor LSTM outputs prediction on each sub-sequence. The final outcome is obtained by reconstructing the prediction results of sub-sequences (Bai et al., 2019b).

In air pollutant prediction, lack of data in certain sites happens a lot and deep learning methods cannot perform well on insufficient training data. A good option is to integrate the transfer learning techniques into deep learning methods (Ma et al., 2019, 2020b; Fong et al., 2020). The transfer learning mechanism uses the similarity between two different but related datasets or models, and transfers the knowledge learned from the source domain to the target ones (Pan and Yang, 2009; Ye and Dai, 2018). It is particularly fits the situation when the number of samples is limited or the modeling process is complicated in the target domain. A deep learning model that has been well trained on sufficient data can be reused as the starting point of a model facing the similar task with insufficient data. Ma et al. exploited a model-based Transfer Stacked Bidirectional Long Short-Term Memory network (TLS-BLSTM) to predict air pollutants at new sites that lack data. A stacked BLSTM network had been pre-trained with large amounts of data from existing sites. Then some of its hidden layers were frozen, and the parameters in the remaining hidden layers were fine-tuned with a small amount of data from the new sites. In this way, the model retained the useful information learned from the existing sites, and boosted the prediction on the new sites (Ma et al., 2020b).

Statistical methods can also be added to deep learning methods to improve the effectiveness of air pollutant concentration prediction (Xu et al., 2021; Ma et al., 2020a; Kim et al., 2021; Gu et al., 2022; Chen et al., 2021a; Han et al., 2022). For example, Kim et al. took advantage of the hierarchical clustering method to classify sites in the study region and then feature selection method was used to evaluate the importance of each input feature in deep learning model. Some redundant features irrelevant to prediction are eliminated. The addition of the clustering and feature selection methods improves the $PM_{2.5}$ prediction accuracy on 1-h, 6-h and 10-h ahead (Kim et al., 2021). Gu et al. integrated the Non-linear Auto Regressive Moving Average technique, automatic feature generation and feature selection methods into a deep learning model for $PM_{2.5}$ prediction. The experimental results demonstrate the superiority of proposed model over single deep learning model in prediction accuracy for peak values (Gu et al., 2022). Table 6 lists typical literatures of deep learning combined with other technologies for air pollutant prediction.

4. Public datasets

High-quality datasets are important for accurate prediction of air pollutant concentration. In this section, we summarize public datasets for air pollutant prediction. The summary is presented in two parts: part A includes the published spatio-temporal sequential data and part B lists some auxiliary features that are often used to improve the accuracy of air pollutant prediction model. Due to different structures of models, these auxiliary features cannot be applied to all models.

4.1. Public datasets

We list currently well-maintained public datasets that store real data of air pollutant concentrations.

CNEMC The dataset of China National Environmental Monitoring Centre (CNEMC) belongs to the Ministry of Ecology and Environment of the People's Republic of China (http://www.mee.gov.cn/). CNEMC has collected air pollutant concentration data of 375 cities or regions and

Table 6
Literature classification for deep learning combined with other technologies for air pollutant concentration prediction.

Other technology	Deep learning model	Literatures
WT and its variants	RNN	(Cabaneros et al., 2020; Zeng et al., 2022; Cheng et al., 2021)
EMD and its variants	RNN, TCN	(Huang et al., 2021b; Bai et al., 2019b; Jiang et al., 2021; Wang et al., 2022b)
Transfer learning	RNN	(Ma et al., 2019, 2020b; Fong et al., 2020)
Statistical methods	Various deep learning methods	(Xu et al., 2021; Ma et al., 2020a; Kim et al., 2021; Gu et al., 2022; Chen et al., 2021a; Han et al., 2022)

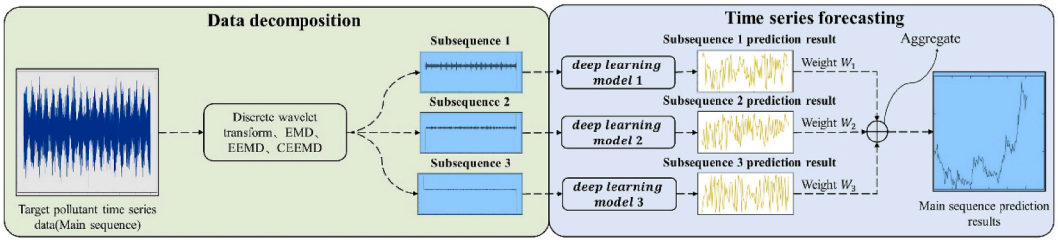

Fig. 3. Framework for the hybrid method based on the data decomposition and deep learning methods.

2023 monitoring sites throughout China since Jaunary 1st, 2021. The source is available at: https://quotsoft.net/air/or https://www.aqistudy.cn/historydata/.

UCI Machine Learning Repository The UCI Machine Learning Repository is a collection of databases that are used by research on machine learning algorithms. Three datasets of it, Beijing $PM_{2.5}$ Data, Beijing Multi-Site Air-Quality Data and $PM_{2.5}$ Data of Five Chinese Cities, record air pollutant concentrations. The source is available at: https://archive.ics.uci.edu/ml/datasets.php.

Beijing $PM_{2.5}$ Data It contains the hourly $PM_{2.5}$ data monitored at the US Embassy in Beijing, and meteorological data monitored at Beijing Capital International Airport from Jan 1st, 2010 to Dec 31st, 2014.

Beijing Multi-Site Air-Quality Data It records six air pollutants and six relevant meteorological variables that were hourly measured by 12 national monitoring sites in Beijing from Mar 1st, 2013 to Feb 28th, 2017.

$PM_{2.5}$ Data of Five Chinese Cities It gleaned $PM_{2.5}$ and meteorological data from Beijing, Shanghai, Guangzhou, Chengdu and Shenyang. from Jan 1st, 2010 to Dec 31st, 2015.

Urban Air Urban Air dataset is constructed by Microsoft Research. It contains data from four cities, Beijing, Tianjin, Guangzhou and Shenzhen, and 39 neighboring cities within 300 km from them from May 1st, 2014 to Apr 30th, 2015. In total, there are 2,891,393 air quality records measured hourly by 437 air quality monitoring sites, 1,898,453 meteorology records collected hourly at a district (or city) level, and 910,576 weather prediction records of two coming days with a district (or city)-level and a temporal granularity of 3 h, 6 h, or 12 h. The source is available at http://research.microsoft.com/apps/pubs/?id=246398.

AirNet AirNet dataset consists of data of SO_2, $PM_{2.5}$, PM_{10}, NO_2, CO, O_3 and AQI collected from 1498 sites as well as meteorological data in China. The data in AirNet are four-dimensional containing information of latitude, longitude, timesteps, features, ranging from Apr 1st, 2015 to Sep 1st, 2017. For each timestep, there are six meteorological features and seven air quality indices. A processed version is available at: http://airnet.caiyunapp.com.

G.Zou This dataset contains historical pollutant concentration and meteorological data from monitoring sites in 10 cities collected from May 13th, 2014 to May 30th, 2018 (http://github.com/zouguojian/data). The data in it is city level, that is, the sample data of each city of every hour is a one-dimensional feature vector composed of seven pollutants, including SO_2, $PM_{2.5}$, PM_{10}, NO_2, CO, O_3 and AQI, and nine meteorological factors. Ten cities throughout China are selected, Shanghai, Nanjing, Hangzhou, Wuhan, Beijing, Shenyang, Harbin, Chengdu, Wulumuqi, and Lasa.

DEFRA It depicts the whole air quality picture of the United Kingdom, containing pollutant concentration (SO_2, $PM_{2.5}$, PM_{10}, NO_2, O_3) data collected from more than 1500 sites. There are two major types: automatic monitoring sites and non-automatic monitoring sites. The oldest data from the automatic monitoring sites go back to 1972, and the oldest from the non-automatic monitoring sites trace back to 1961. The source is available at: https://uk-air.defra.gov.uk.

EPD EPD dataset contains data collected from 18 air quality monitoring sites in Hong Kong. These sites can be divided into two categories, general sites and roadside sites. Each monitoring site records the hourly, daily mean, monthly average and yearly average air pollutant concentration (SO_2, $PM_{2.5}$, PM_{10}, NO_2, CO, O_3 and NO_x) data, from 1990 to 2021. The data are available at: https://cd.epic.epd.gov.hk/EPICDI/air/station/?lang=en.

US EPA It stores daily air pollutant concentration data (SO_2, $PM_{2.5}$, PM_{10}, NO_2, CO, O_3 and Pb) from outdoor monitors across the United States, Puerto Rico, and the U. S. Virgin Islands from 1980 to 2021. The source is available at: https://www.epa.gov/.

TW EPA This dataset contains hourly data of SO_2, $PM_{2.5}$, PM_{10}, NO_2, CO and O_3 from more than 75 monitoring sites in the Taiwan Main Island, ranging from 2018 to 2022. The source is available at: https://www.epa.gov.tw/.

Air Korea Air Korea dataset collects air pollutant concentration data from monitoring points in various cities in South Korea, including major cities like Seoul and Busan. The web address of the paper providing the relevant data is: https://www.mdpi.com/2071-1050/12/19/8014.

CPCB CPCB dataset collects data from 703 air quality monitoring sites. These sites are located in 307 cities/towns of 29 states and 6 Union Territories in India, out of which 78 sites are in Delhi. The time interval for the collected data is 15 min. The URL of the paper providing the data is: https://www.sciencedirect.com/science/article/pii/S2212095521000304.

4.2. Auxiliary features

Prediction on air pollutant concentrations can be affected by some complicated factors, usually called auxiliary features. We list some auxiliary features considered by most researchers.

Meteorological factors: Studies have shown that air pollutants vary under different meteorological conditions, e.g., the temperature affects the atmospheric and ventilation conditions; humidity and precipitation can change the deposition characteristics of particulate matter; wind speed promotes the diffusion and spread of pollutants (Feng et al., 2015; Saide et al., 2016). In addition, the following meteorological factors can also cause different degrees of impact: dew point, pressure, wind direction, rainfall, snowfall, solar radiation, net radiation, clouds, conds, visibility, weather (Zhang et al., 2021a).

Chemical mechanism factors: The formation process of air pollutants is quite complex and variable, containing several chemical reactions. For example, Nitrogen oxides and volatile organic compounds can interact photochemically under favorable meteorological conditions to produce surface ozone (Sousa et al., 2007). Therefore, chemical reactions between pollutants and between pollutants and other substances can change pollutant concentrations. Some chemical materials can be taken into account when making air pollution predictions, e.g., Nitrous oxide, Ammonia, Ozone, Sulfur dioxide, Carbon dioxide, Carbon monoxide, Nitrogen dioxide, $PM_{2.5}$, PM_{10}, Organic compound (Abdul-Wahab, 2001; Zhao et al., 2019; Mo et al., 2020).

Traffic factors: Traffic emissions have been one of the contributors to air pollution in many cities around the world and can deteriorate ambient air quality on a large spatial scale, especially during the morning and evening rush hours in urban regions (Wu et al., 2017). With this in mind, the researchers included traffic-related data in their air pollution predictions (Kaya and Öğüdücü, 2020; Crouse et al., 2009).

POI factors: point of interests (POIs) refer to the unique features of a particular region. The category and density of POIs in the region indicates the land use and function of the region, thus contributing to the prediction of air pollution in this region. Some POIs are even directly related to changes in air pollution. For example, if an region is industrial, its air quality is usually bad; if a park exists in an region, its air quality will become good (Zheng et al., 2013). Some of the POIs categories that are frequently used by researchers are vehicle services (gas stations, repair), factories, decoration and furniture markets, food and beverage, shopping malls and supermarkets, parks, etc. (Zheng et al., 2013).

Regional geographic factors: Studies have shown that air pollution in sites is highly correlated. when the right neighboring districts are selected, or when the distance-based selection of neighboring regions is applied, the geographic prediction models are superior to non-geographic models (Kurt and Oktay, 2010). These geographical factors relate to: the longitude and the latitude of air quality ground monitoring sites or cities, the distance between monitoring sites or cities (Qi et al., 2019).

Temporal factors: The purpose of introducing temporal factors is to allow the model to better identify the patterns of change in the temporal dimension of historical data and thus accurately capture the dynamic temporal correlation. The main temporal factors include: seasons, days of a week, time of a day (Bai et al., 2019a; Jiang et al., 2021):

- The monitoring season is mapped using one to four.
- Days of a week includes weekdays (Monday to Friday) and weekends (Saturday and Sunday) according to their different characteristics.
- Time of the day is represented by 24 time points indicating 24 h of a day.

5. Experimental analysis

In this section, we compare the experiments that the deep learning and non-deep learning methods have conducted on the public datasets and draw some conclusions from the comparison.

5.1. Model performance evaluation indicator

Two indicators are usually used to evaluate prediction performance of the models: Rooted Mean Squared Error (RMSE) and Mean Absolute Error (MAE). They are defined as:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\hat{y}_i - y_i)^2} \tag{8}$$

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n}|\hat{y}_i - y_i| \tag{9}$$

where y_i is the observed value of the air pollutant concentration, while $\hat{y}_i$ is the predicted value; and n is the number of samples in the test set. RMSE measures model's stability: smaller value implies higher stability. MAE indicates the total error between the predicted value and the observed one. The smaller value of MAE reflects the higher prediction accuracy of the model.

5.2. Experimental analysis on public datasets

In the pollutant concentration prediction task, the dataset is generally divided into the training set, validation set, and test set, or training set and test set. The training set is used for model learning, the validation set is used to determine hyperparameters, and the test set is used to verify the model's performance or to determine hyperparameters. For the model parameter selection process, non-deep learning methods are initialized by prior knowledge and experience, while deep learning methods are trained by continuously trying the settings of hyperparameters to select the optimal hyperparameter combination. There will be differences in hyperparameters between models for the same dataset, but they are all close to optimal for each study.

Therefore, there are inevitably differences in hyperparameter configurations, but this does not affect comparing the best prediction performance between these methods. We summarized deep learning and non-deep learning models that have been tested on the 11 public datasets. Non-deep learning models include two main categories: statistical and deterministic methods. The final results are listed in Table 7 and Table 8, where the prediction granularity in Table 7 is hours and in Table 8 is days.

According to the different pollutant concentration prediction tasks, we divide the prediction tasks into single- and multi-step prediction, as shown in Fig. 4. Where x_{t-r+1} denotes the historical observations of the past $t-r+1$ timestep, used as inputs to the model. $\hat{y}_{t+n}$ and $\hat{y}_{t+m}$ are the model's predicted values for future timestep $t+n$ and $t+m$, respectively. Some models output single value for predicting air pollution concentration at one timestep in the future, which is called single-step prediction. Multi-step prediction means that models outputs multiple values that are used to predict target pollutant concentrations at multiple timesteps ahead simultaneously. Furthermore, we unified single- and multi-step prediction tasks for target pollutants under the public datasets to provide a more valuable comparison. These selected prediction tasks are the most studied by researchers and representative. Based on the experimental results on the public datasets (Huang et al., 2021a; Zhang et al., 2021a, 2022a; Zhou et al., 2017; Zhao et al., 2020; Krishna Rani Samal et al., 2021a, 2021b; Pak et al., 2020), (Jia et al., 2021; Ma et al., 2020a, 2020b; Shi et al., 2021; Jiang et al., 2021; Singh et al., 2012; Huang et al., 2021b; Mengara et al., 2020; Wen et al., 2019), (Abirami and Chitra, 2021; Liao et al., 2015; Qiao et al., 2021; Cai et al., 2009; Jin et al., 2019; Mao et al., 2022; Xiao et al., 2020, 2021a, 2021b; Wang et al., 2022c; Garg and Jindal, 2021; Lu et al., 2021b; Aggarwal and Toshniwal, 2021; Espinosa et al., 2021; Tao et al., 2019; Zheng et al., 2015; Zhang et al., 2017; Bhagat and Saha, 2021; Lee et al., 2022; Sahu et al., 2020; Jat et al., 2021; Li et al., 2019; Zhu et al., 2019; Fan et al., 2017; Wood, 2022; Smyth et al., 2009; Kelly et al., 2019; Jena et al., 2021; Hong et al., 2022; Liu et al., 2018; Kow et al., 2022; Wong et al., 2021), some interesting findings can be drawn from Tables 7 and 8:

Table 7
Prediction performance of different models on public datasets at hourly granularity.

Dataset	Air pollutants	Prediction task		RMSE			MAE		
		Single-prediction	Multi-prediction	DL Model	Statistic Model	Deterministic Model	DL Model	Statistic Model	Deterministic Model
CNEMC	$PM_{2.5}$	T+1h	T+(1–24) h	1.11[121]/ 17.83[95]	5.26[121]/ 80.16[157]	14.75 [181]/35.80 [24]	0.66[121]/ 9.68[95]	3.49[121]/ 55.11[157]	11.42[181]/29.82 [160]
	PM_{10}	T+1h	T+(1–5) h	7.13 [155]/ 7.98[155]	20.70[156]/ 57.50[156]	71.50[154]/N	16.55[174]/ 23.72[174]	15.50[156]/ 35.00[156]	N
	O_3	T+1h	T+(1–24) h	10.04[119]/ 22.08[161]	14.56 [119]/N	26.11 [105]/N	8.09[119]/ 16.11[161]	21.84[162]/N	22.61[105]/28.17 [160]
	NO_2	T+1h	T+(1–12) h	6.65[62]/ 19.55[172]	7.71[62]/ 16.00[173]	N/17.13[159]	4.56[62]/ 13.82[172]	5.46[62]/ 15.00[173]	N/12.86[159]
Air Net	NO_2	T+1h	T+(1–24) h	1.63[60]/ 9.72[164]	2.12[60]/ 15.14[164]	N	1.30[60]/ 7.04[164]	1.63[60]/ 10.60[164]	N
US EPA	$PM_{2.5}$	T+1h	——	3.48[117]	4.67[117]	7.36[177]	1.85[117]	2.68[117]	9.80[176]
UCI	$PM_{2.5}$	T+1h	T+(1–2) h	11.23[84]/ 11.83[84]	20.84[84]/ 27.64[165]	N	6.46[84]/ 7.70[84]	11.44[84]/ 16.72[165]	N
Urban Air	$PM_{2.5}$	T+1h	T+(1–25) h	11.31[10]/ 37.80[10]	15.50[10]/ 49.61[10]	23.21[167]/ 118.77[167]	6.52[10]/ 26.04[10]	10.62[10]/ 30.05[10]	8.15[167]/57.45 [166]
G .Zou	$PM_{2.5}$	T+1h	T+(1–24) h	5.60[11]/ 22.30[11]	19.02[11]/ 41.80[11]	34.09[11]/36.30 [11]	3.20[11]/ 15.50[11]	13.28[11]/ 30.00[11]	N
DEFRA	$PM_{2.5}$	T+1h	——	3.45[175]	7.31[175]	N	2.35[175]	5.48[175]	N
Air Korea	$PM_{2.5}$	T+24h	——	6.93[93]	13.49[93]	21.16[169]	5.07[93]	9.03[93]	7.38[169]
CPCB	$PM_{2.5}$	T+1h	T+(1–24) h	6.67[153]/ 12.00[61]	12.98[81]/ 33.00[61]	10.99[170]/50.00 [171]	3.94[153]/ 12.00[61]	10.31[81]/ 31.00[61]	9.79[170]/N

Table 8
Prediction performance of different models on public datasets at daily granularity.

Dataset	Air pollutants	Prediction task		RMSE			MAE		
		Single-prediction	Multi-prediction	DL Model	Statistic Model	Deterministic Model	DL Model	Statistic Model	Deterministic Model
CNEMC	$PM_{2.5}$	T+1day	T+(1–8) days	3.00[8]/43.14 [178]	20.28[74]/ 48.10[162]	46.50[179]/N	2.21[8]/29.15 [178]	14.98[8]/30.77 [178]	N
	O_3	T+1day	T+(1–3) days	17.43[158]/ 18.13[158]	26.74[139]/ 30.91[139]	27.90[24]/27.03 [24]	12.35[158]/ 13.02[158]	20.38[158]/ 23.29[158]	21.90[24]/21.10 [24]
EPD	O_3	T+1day	\	16.47[118]	18.32[118]	19.30[182]	12.75[118]	13.67[118]	N
	NO_2	T+1day	\	14.10[118]	15.96[118]	16.70[182]	10.35[118]	11.32[118]	N
	$PM_{2.5}$	T+1day	\	6.74[118]	7.46[118]	8.60[182]	4.92[118]	5.19[118]	N
UCI	$PM_{2.5}$	T+1day	T+(1–9) days	17.20[161]/ 12.00[63]	19.90[161]/ 57.00[63]	N	11.90[161]/ 10.00[63]	12.30[161]/ 52.00[63]	N
CPCB	$PM_{2.5}$	T+1day	T+(1–9) days	10.60[163]/ 15.00[63]	12.35[168]/ 68.00[63]	131.13[180]/N	5.45[163]/ 12.00[63]	8.52[168]/ 58.00[63]	N
TW EPA	$PM_{2.5}$	T+1day	T+(1–3) days	7.12[183]/ 7.97[183]	9.72[184]/N	10.03[183]/10.15 [183]	4.59[183]/ 5.27[183]	6.09[184]/N	7.02[183]/7.14 [183]

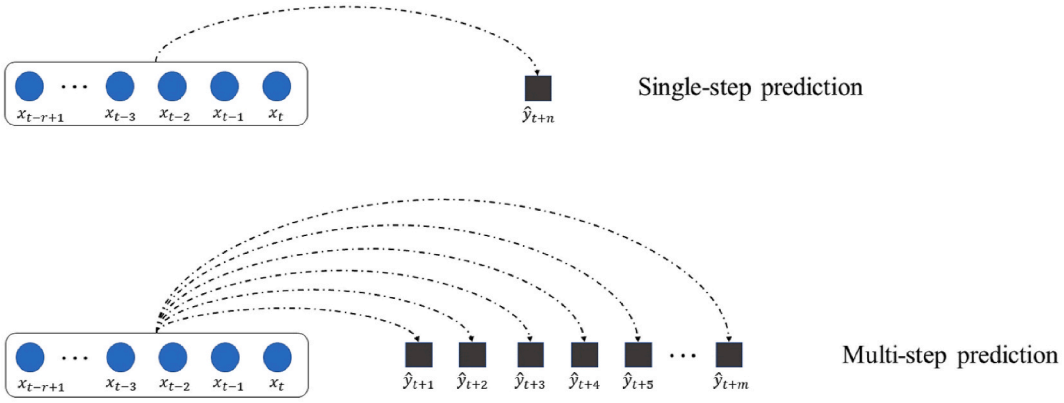

Fig. 4. Single-step and multi-step prediction.

- For the prediction of the same target pollutant concentration on the same dataset, the single-step prediction performed better than the multi-step prediction. Tables 7 and 8 show that whether deep learning, statistical or deterministic models, their single-step predictions for target pollutants in all datasets almost outperformed multi-step predictions. Especially for the $PM_{2.5}$ prediction under the Urban Air dataset, the RMSE value of deep learning, statistical, and deterministic models in single-step prediction of the next hour was reduced by 70.08%, 68.76% and 80.46% and the MAE value was reduced by 75.02%, 64.66% and 85.81% respectively, in contrast with their multi-step prediction of the next 1–25 h. The performance of multi-step prediction is lower than that of single-step prediction, and the reasons can be summarized in two aspects: on the one hand, since the period of multi-step prediction is much larger than that of single-step prediction, the historical data that needs to be referenced is more and broader. On the other hand, there is an error propagation situation in multi-step prediction, and as the prediction timestep increases, the prediction error will gradually accumulate.
- Deep learning methods perform better than non-deep learning ones on single- or multi-step predictions. As can be seen from Table 7, when the prediction granularity is hours, the RMSE and MAE values of the deep learning model decrease in different degrees compared to the statistical and deterministic models for both single-step and multi-step prediction. For example, in the 1-h ahead prediction of $PM_{2.5}$ on the US EPA dataset, the RMSE values of the deep learning models were reduced by 25.48% and 52.72% compared to the statistical and deterministic models, respectively. The MAE values decreased by 30.97% and 81.12%, respectively, compared to the other two types of models. Similarly, it can be seen from Table 8 that, in the 1–3 days ahead prediction of O_3 on the CNEMC dataset, the RMSE values of the deep learning models decreased by 41.35% and 32.93%, and the MAE values reduced by 44.10% and 38.29%, compared to the statistical and deterministic models. The main reasons are the following: First, non-deep learning methods are inept at determining the complex, non-linear relationships in data due to their limited structure; second, non-deep learning methods are not suitable for large-scale datasets because they are restricted by model complexity. For deep learning methods, their flexible and complex structures help them break through the above constraints of non-deep learning methods. They perform better both on single-step and multi-step prediction for air pollutant concentration.

In addition, we have done research on two other perspectives. We investigated the impact of seasonal changes in pollutants on the prediction performance of these models. The performance indicators of the models which act on the target pollutants of the commonly used public datasets are summarized in four seasons: spring, summer, autumn and winter. The final results are presented in Table 9. In the category of deep learning models, we also explored the performance of hybrid models compared to single models on the target pollutants of the commonly used public datasets. The results are shown in Table 10.

Studies have shown that the change of seasons can have an impact on air pollution (Bai et al., 2019a; Mattos Neto et al., 2014). Different seasons are accompanied by different climatic conditions and human activities such as low temperature and low wind speed winter atmospheric conditions, coal burning and firecrackers in winter, which lead to changes in air pollution (Ye et al., 2016). Therefore, researchers usually consider seasonal influence factors when conducting air pollution prediction studies. This is done by dividing the dataset into four datasets: spring, summer, autumn, and winter, and then exploring the

Table 9
Predictive performance of different models on commonly used public datasets under the influence of seasonality.

Method	Dataset	Target pollutants	Prediction task	Performance Index (RMSE/MAE)			
				Spring	Summer	Autumn	Winter
DL Model	**CNEMC**	$PM_{2.5}$	T+1 h	10.28[66]/8.01[66]	6.70[66]/5.60[66]	23.97[66]/17.65[66]	34.56[66]/24.76[66]
Statistic Model			T+1 h	2.14[185]/1.51[185]	3.20[185]/2.59[185]	5.45[185]/4.54[185]	9.61[185]/7.61[185]
Deterministic Model			T+ (1–24) h	17.05[186]/N	17.04[186]/N	18.18[186]/N	13.67[186]/N
DL Model	**EPD**	O_3	T+1 day	9.83[187]/N	11.91[187]/N	10.13[187]/N	8.79[187]/N
Statistic Model			T+1 day	14.10[188]/10.64 [188]	N	21.38[188]/14.23 [188]	8.48[188]/6.78[188]
Deterministic Model			\	N	N	N	N
DL Model	**UCI**	$PM_{2.5}$	T+1 h	9.17[189]/N	7.14[189]/N	7.15[189]/N	9.06[189]/N
Statistic Model			T+(1–2) h	20.58[190]/16.11 [190]	17.61[190]/7.83[190]	28.42[190]/25.56 [190]	27.65[190]/22.99 [190]
Deterministic Model			\	N	N	N	N
DL Model	**CPCB**	$PM_{2.5}$	T+1 h	3.800-3.825[153]/N	3.825-3.850[153]/N	3.775-3.800[153]/N	3.850-3.875[153]/N
Statistic Model			T+1 day	18.26[191]/15.33 [191]	18.26[191]/15.33 [191]	22.97[191]/17.28 [191]	17.29[191]/13.56 [191]
Deterministic Model			T+1 day	40.80[192]/14.57 [192]	49.90[192]/11.80 [192]	46.94[192]/14.43 [192]	38.57[192]/14.27 [192]

Table 10
Performance comparison of hybrid models and single models with commonly used public datasets among deep learning methods.

Dataset	Target pollutant	Prediction task	Model	RMSE	MAE
CNEMC	$PM_{2.5}$	T+(1–24) h	C-LSTME [95]	17.83	9.68
			LSTME [95]	29.61	14.20
EPD	O_3	T+1 day	SA-LSTM [118]	16.47	12.75
			LSTM, GRU, Original RNN [118]	17.85	13.55
G .Zou	$PM_{2.5}$	T+(1–24) h	EDS Model [11]	22.30	15.50
			GRU, RNN, LSTM, Bi-LSTM [11]	36.25	25.43
UCI	$PM_{2.5}$	T+1 h	EMD-GRU [84]	11.23	6.46
			RNN, LSTM, GRU [84]	20.76	11.14
US EPA	$PM_{2.5}$	T+1 h	Lag-LSTM [117]	3.48	1.85
			RNN, LSTM [117]	4.59	2.52

predictive performance of deep learning and non-deep learning models on each of the four datasets, as shown in Table 9 (Bai et al., 2019a; Abirami and Chitra, 2021; Li et al., 2018b, 2022b; Hong et al., 2020; Ma et al., 2022b; Wang and Lu, 2006; Chen et al., 2021b; Barthwal et al., 2021; Kota et al., 2018). As a result, the values of RMSE and MAE show that some researchers have improved the prediction accuracy by including seasonal effects as a reference whether using deep learning, statistical or deterministic models. For example, combining Tables 7 and 9, in the prediction of $PM_{2.5}$ for the next hour based on the UCI dataset, the best prediction performance of the deep learning model occurs in the summer prediction (Chen et al., 2021b); compared to the deep learning model without considering the seasonal effect (Huang et al., 2021b), the RMSE value decreased by 36.42%. This proves that seasonal variation has some effect on the prediction performance of the three models.

Among deep learning methods, the hybrid methods formed by multi deep learning models often perform better than those with a single deep learning model for air pollutant concentration prediction on single- and multi-step tasks on commonly used public datasets (Zhang et al., 2021a; Wen et al., 2019; Shi et al., 2021). For example, as shown in Table 10, the Convolutional and Long Short-Term Memory Neural Network Extended model (C-LSTME) (Wen et al., 2019) consisting of 3D-CNN and LSTME outperformed single LSTME model on CNEMC dataset for 1–24 h ahead prediction task facing $PM_{2.5}$, with RMSE and MAE reduction of 39.78% and 31.83%, respectively. Methods with a single deep learning model generally consider only one aspect of factors, temporal or spatial, for prediction; while the hybrid models can often extend the strengths of single deep learning models and simultaneously extract complex and non-linear spatio-temporal correlations. In addition, hybrid models integrating deep learning models and other technologies can also surpass methods with a single deep learning model in some prediction tasks (Huang et al., 2021b; Ma et al., 2020a). From Table 10, a hybrid model based on EMD and GRU defeated a single RNN, LSTM, and GRU network when predicting $PM_{2.5}$ concentrations at sites in Beijing in the next hour with RMSE and MAE values reduced by 45.91% and 42.10%, respectively (Huang et al., 2021b). This is because deep learning models are not foolproof due to the limitations of input data, parameter optimization, model structure. In some cases they don't work very well (Huang et al., 2021b; Xu et al., 2021; Cabaneros et al., 2020; Zeng et al., 2022; Cheng et al., 2021; Bai et al., 2019b; Ma et al., 2019, 2020a, 2020b; Jiang et al., 2021; Wang et al., 2022b; Fong et al., 2020; Kim et al., 2021; Gu et al., 2022; Chen et al., 2021a; Han et al., 2022). Thus, in the prediction process, we can consider introducing other techniques to make up for the deficiencies of deep learning models in these aspects, improving the prediction performance.

6. Limitations and future directions

Although deep learning technology has made great progress in air pollutant concentration prediction, there are still some challenges worth exploring. In this Section, we discuss the limitations of current studies and identify some directions for future research.

6.1. Limitations

Data shortage Models based on deep learning require a large amount of data to achieve excellent prediction results, but data for air pollution prediction are not always sufficient. For example, extreme situations, like inclement weathers or equipment maintenance, often interrupt data collection; and air-related records in some areas are gleaned intermittently due to their under-developed air-quality monitoring systems. Insufficient training data have weakened the performance of deep-learning models. Some researchers have utilized the transfer learning technology to tackle this problem (Ma et al., 2019, 2020b; Fong et al., 2020). This technique aims to transfer knowledge from regions with rich data sources to target regions with scarce data. Despite its effectiveness, it still needs further exploration, such as, how to design a high-quality mathematical model to match two regions, etc., still need to be explored.

Long-term prediction Most deep learning methods focus on short-

or medium-term prediction of air quality, and a few of them delve into long-term tasks (Tu et al., 2021). Long-term prediction involves more complex and flexible spatio-temporal correlations and more uncertain factors. The principle of conducting it also differ from the short or medium tasks: the effect of historical data may decrease and multiple, still-unclear features may be encompassed.

High-dimensional data Most raw data that current deep learning methods use for air quality-assessment are in a single dimension, and other impact factors, like, land usage, forest coverage rate, populations, etc., have not been sufficiently considered. Although higher-dimensional data that fuse multi-factors can elevate air pollution prediction, the costs are huge. Current algorithms cannot afford "curse of dimensionality" and expensive computational consumption, and how to choose appropriate number of suitable factors is a problem to be solved.

Baseline for performance evaluation Given the flexible but similar architecture, most deep learning methods work and construct in a similar way for air-quality assessment. It is quite difficult to compare these models in a more comprehensive and detailed way without a standardized baseline that consists of definitive experiment settings and datasets. Meanwhile, as the complexity of the models is increasing, the efficacy of each component has become more ambiguous, although ablation studies can be used for discussion.

Interpretability problem Models based on deep learning have been suffering the black box problem from the day their were born. Their working procedures are uninterpretable due to their complex structure and a large number of parameters. Although they output more accurate prediction results than non-deep learning models, the reason for this and the procedures for determining parameters are still unclear. How to construct a deep learning model with high interpretability is a problem urgently to be solved.

Expensive computing costs Models based on deep learning usually require GPU or TPU to fulfill their computation instead of CPUs. In addition, with the rising number of parameters, they also cost much more memory. How to ensure that deep learning models do not consume too much computational resources with the same training and testing results deserves to be further explored.

6.2. *Future directions*

Selection of optimal model As various methods can be a choice for one prediction task, a set of well-accepted criteria for the selection is still required. At present, RNNs are usually used to deal with one-location historical data, and CNNs, GCNs and Spatial Attention Mechanism are commonly developed for multi-location data. But how to choose an appropriate one for a new task to obtain the possible max prediction performance is still an open question.

Prediction under noises Some raw data of air quality recorded by monitoring sites usually deviate from true vales due equipment failures or environmental impact. These noise-contaminated data may influence the final prediction of deep learning methods. Currently, data processing and model prediction are separated as two independent procedures to avoid noise impact. It is of great significance to build a robust model that could effectively tackle this problem.

Intergradation into the Internet of Things in smart cities Smart city is an intelligent system that connects all independent units in a city together through the technology of Internet of Things (IoTs) (Singh et al., 2020). This system can collect and process large amounts of real-time data and help decision makers present better strategies (Mazhar Rathore et al., 2018). Integrating air quality prediction function into a smart city is a promising direction for the research of deep learning-based air pollution prediction.

Diversified data collection National monitoring sites are major source of air quality data. It is not enough and some researchers have proposed new devices for collecting data, such as smart mobile pollution monitoring devices and low-cost air pollution sensors (Mihăiţă et al., 2019). These devices are promising, and encompassing their data into the historical information will improve the accuracy of deep learning prediction. The diversified data can also compose a massive knowledge database for further exploitation.

Application of distributed computing Although the deep learning model has made great achievements in air pollutant concentration prediction, its slow training speed is still a problem. Distributed computing has been verified an effective alternative to improve the training speed of these models (Ramon-Cortes et al., 2021). For example, Apache Spark framework (Asgari et al., 2017) is a popular tool that can process large-scale data in a distributed way. It might be promising to combine distributed computing with deep learning technology for air pollutant concentration prediction.

7. Conclusion

We conduct a comprehensive review on deep learning methods for air pollutant concentration prediction. We classify the existing methods and review the air pollutant concentration prediction based on non-deep learning from the aspects of characteristic, application and limitation of prediction method. Furthermore, we summarize the methods based on deep learning from perspectives of temporal, spatial, spatio-temporal and its variants. We enumerate the major public datasets and representative experimental results in different prediction tasks based on listed datasets to compare the prediction performance of non-deep learning and deep learning methods and draw some conclusions. Finally, we put forward some limitations and future research directions that are worthy of reference. This paper provides an overview on the research progress of air pollutant concentration prediction, and could be a useful reference for researchers in this field.

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.

Data availability

No data was used for the research described in the article.

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