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Proactive Asthma Forecasting using Graph Neural Digital Twins

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ABSTRACT

Asthma is a problem that people have to deal with every day. It is a disease that affects the lungs and airways. It can cause a lot of trouble. Sometimes people have to go to the hospital because of it. It can make their life really hard. Asthma can be understood with the help of devices that people can wear machines that can check the air and environment and computers that can think like people. The old ways of predicting when asthma will get worse are not very good. They only look at a things like what is happening in the body or what is in the air and they do not see how all these things work together. This paper is about a way of predicting when asthma will get worse. We call it the Graph Neural Digital Twin Framework. It is like a computer program that looks at lots of things like what the body is doing what the air is like what kind of medicine people are taking and even what the weather is like. It puts all these things into a map, like a graph and then it uses that map to figure out when asthma might get worse. people can prevent their asthma from getting worse. And it has another part that can explain why it made predictions so people can understand what is going on. When we tested this program it worked well. It was better than programs that are used for this kind of thing and it was very accurate. It got the answer 98.76% of the time and it was very good at finding the people who were really at risk.

Keywords: Graph Neural Networks, Digital Twin, Asthma, Multimodal Learning, Counterfactual AI, Explainable AI

1. INTRODUCTION

Asthma is a common disease that affects peoples lungs and it is a big problem for a lot of people. Over 260 million people around the world have asthma. Asthma causes a lot of problems because people have to go to the hospital a lot. They do not feel well. The asthma attacks happen because of things like how a persons body is, what is around them if they take their medicine and how they live. So doctors have a time knowing when someone will have an asthma attack. They usually just treat the person after they have an attack of trying to stop it from happening. Now we have some tools like the Internet of Medical Things and special watches that can track what is going on with our bodies. We also have computers that keep track of our health information and machines that can check the air and weather. All of these things give us a lot of information about our health and the world around us, like how we're breathing our heart rate and the air quality. This information can help us make systems that can tell when someone might have an asthma attack before it happens. But most of the systems that use machine learning and deep learning do not look at all of the information together they just look at one or two things. They do not understand how all of these things are connected and affect asthma. Asthma is a disease and we need to look at all of the factors that affect asthma to really understand it and help people with asthma.

Graph Neural Networks have become a good way to learn about complicated relationships in data that is organized like a graph. This is helpful because it can look at how things like a persons physical condition the environment around them and their personal characteristics interact with each other. By doing this Graph Neural Networks can make predictions than traditional models. At the time Digital Twin technology allows us to create virtual copies of patients that are updated all the time with new sensor data, medical history and information about their environment. These personalized virtual copies help us keep an eye on patients continuously understand how their disease is progressing and even predict what might happen to their health in the future. Some recent studies have shown that combining Graph Neural Networks with Digital Twins can be really powerful for healthcare applications. This includes things like personalized monitoring and helping doctors make decisions, about patient care as we can see in studies [1] [4] [6] [7]. Graph Neural Networks and Digital Twins can work together to make healthcare more personalized and effective.

Asthma is a problem and even with new ways to predict it we still have a long way to go. The old systems are not good enough because they do not use all the information they can get from sources they do not make models that are just for one person they are hard to understand and they do not help doctors make plans to stop asthma attacks before they happen. Most of the time people just try to guess when an asthma attack will happen. They do not give any advice on how to stop it from happening in the first place. To make this better this paper talks about a way to predict asthma attacks using a special computer model called a Graph Neural Digital Twin Framework. This framework uses a lot of information like what is happening in a persons body what is in the air they breathe their medical history, what medicine they take and other things to make a special model just for them. It uses a kind of computer program to look at how all these things are connected and to guess when an asthma attack might happen. It also tries to figure out what would happen if the person did something like taking a different medicine or staying inside when the air is bad. The computer program also tries to explain why it made each guess so doctors can understand what is going on.

2. RELATED WORKS

Recent advances in Artificial Intelligence, wearable healthcare technologies and Digital Twins have greatly improved how we predict and manage respiratory diseases like asthma. There are five areas of research in this field- Machine learning-based asthma prediction, deep learning approaches, graph Neural Network-based healthcare analytics, Digital Twin-based healthcare, Explainable and counterfactual AI for clinical decision support. Early asthma prediction models used simple machine learning algorithms like Decision Trees, Random Forests and Artificial Neural Networks to classify asthma severity and predict exacerbation risk from health records and clinical parameters. Haque et al. Proposed a neural network that used personalized weather triggers for asthma prediction[2]. This study showed that environmental conditions like weather significantly affect asthma exacerbations. Although these approaches worked well in predicting asthma they mainly relied on structured datasets. They did not fully capture the interactions among physiological factors, environmental factors and behavioral factors. Artificial Intelligence and Digital Twins can help us better understand asthma and other chronic respiratory diseases. Machine learning-based asthma prediction is an area of research in this field. The use of Artificial Intelligence, in healthcare is improving the prediction and management of respiratory diseases.

With the widespread adoption of wearable sensors and the Internet of Medical Things (IoMT), researchers began utilizing deep learning models to analyze continuous physiological signals. Recurrent Neural Networks (RNNs), Long Short-Term Memory (LSTM) networks, and Transformer architectures have been applied for respiratory disease monitoring because of their capability to model temporal dependencies. However, these models treat patient observations as sequential data and often overlook the spatial and relational dependencies among environmental variables, patient characteristics, and physiological measurements, thereby limiting their predictive capability in dynamic healthcare environments.

Graph Neural Networks are really good at helping us understand relationships in healthcare data. Some people like Zhou and his team have done a lot of work to show that Graph Neural Networks can learn from data that is connected in a way using something called message-passing mechanisms[9]. Jiang and Luo have also shown that Graph Neural Networks can be used to make predictions about the future especially when there are a lot of things happening at the same time. Recently people have started using Graph Neural Networks in applications, which has helped us learn more about patients predict diseases and make better healthcare recommendations[10]. The thing that makes Graph Neural Networks so good for forecasting asthma is that they can understand the relationships between patients the signals from their bodies and the environment around them. Graph Neural Networks are really useful for this kind of thing because they can handle all these relationships. Graph Neural Networks are the key to making predictions, about asthma.

The Digital Twin technology is really getting popular because it helps with precision medicine. Some people like Barbiero and others made one of the Digital Twin frameworks for healthcare [1]. They used graphs to show how patients are doing. What is wrong with them. This way doctors can keep an eye on patients and their diseases.

Researchers found out that Digital Twins can be very helpful for people with reathing problems. They used devices that people wear to track what is going on with their bodies. They also looked at what doctors wrote about them and what's in the air around them. Then they made a copy of the patient. There are also Digital Twin systems that help with air quality inside buildings. These systems are very good at helping people with asthma. They keep track of what's in the air and tell people what they can do to stay safe. Some other systems use computer models to help doctors keep an eye on people with breathing problems. They can even predict what might happen to them. Digital Twin technology is really useful for healthcare and it can help people in many ways. Digital Twins are very helpful for people with breathing problems. They can make a big difference, in their lives[6][7].

Environmental monitoring has become another important research direction because asthma attacks are strongly influenced by air pollution, pollen concentration, humidity, and meteorological conditions. Pei *et al.* [3] proposed a multivariate temporal Graph Neural Network for $PM_{2.5}$ forecasting, while Zhu and Shakir [5] employed Spatio-Temporal Graph Convolutional Networks for daily asthma symptom prediction using passive environmental sensing. These studies demonstrate that incorporating environmental intelligence substantially improves forecasting performance compared with physiological data alone. Furthermore, graph-based pollution forecasting models have enabled more accurate estimation of exposure risks, supporting proactive healthcare interventions [8].

Environmental monitoring is another area of research. This is because asthma attacks are heavily influenced by air pollution, pollen levels, humidity and weather conditions. Researchers like Pei and their team have worked on a type of artificial intelligence model to predict $PM_{2.5}$ levels[3]. This model is a multivariate Graph Neural Network. Meanwhile Zhu and Shakir used an approach called Spatio-Temporal Graph Convolutional Networks[6,8]. They used data from environmental sensors to predict daily asthma symptoms. These studies show that using data can greatly improve predictions compared to using only physiological data. Also graph-based models, for predicting pollution have helped estimate exposure risks accurately. This supports healthcare interventions that can be taken proactively. Such studies have shown that environmental intelligence can improve forecasting performance [8].

Explainable Artificial Intelligence is really important for making Artificial Intelligence based systems more transparent and trustworthy in clinics. Doctors need to know how Artificial Intelligence makes decisions. There are ways like LIME [22] and SHAP [23]that help doctors understand how each piece of information affects the outcome. Reasoning to see what would happen if we changed some things. For example what if we reduced how bad stuff someone is exposed to or what if they took their medicine on time or what if they made healthier choices. This can help us guess how those changes might affect their health in the future.

Some people like Pearl have done work on this. It is a big part of making Artificial Intelligence trustworthy in medicine. Explainable Artificial Intelligence studies have shown that counterfactual reasoning is very important for Artificial Intelligence that people can trust[24]. Explainable Artificial Intelligence and Artificial Intelligence are crucial, in this context[25]. There are still some problems with the way we predict asthma. Most of the models we have now look at either what's going on in the body or what is happening in the environment. They do not look at both things together so we do not get a picture of the patient. The current systems that use Digital Twin technology mostly focus on keeping an eye on things than trying to predict what will happen. Some models that use Graph Neural Networks only look at how thingsre related to each other and do not make virtual models of individual patients. Also most systems do not use optimization and explainable AI to suggest ways to prevent asthma attacks.

These problems are why we need the Graph Neural Digital Twin Framework. This framework uses lots of types of data, about the body and the environment. It also uses Graph Neural Networks, Digital Twin technology, Explainable AI and counterfactual optimization. All of these things work together to help us predict when someone might have an asthma attack and to make plans to help them. The Graph Neural Digital Twin Framework is a way to predict asthma attacks and help doctors make good decisions.

3. PROPOSED SYSTEM ARCHITECTURE

The proposed Graph Neural Digital Twin Framework for Proactive Asthma as shown in figure 1 Forecasting is made to keep an eye on people with asthma all the time. It tries to figure out if they're at risk of having a bad asthma attack and suggests things they can do to prevent it. This framework puts together lots of kinds of information about the persons body the air they breathe and their medical history into a special Digital Twin that is just for them. Then it uses a Graph Neural Network to make predictions about what might happen to them.

The Graph Neural Digital Twin Framework for Proactive Asthma Forecasting also has a part that helps explain how it makes its predictions called an Explainable Artificial Intelligence module and another part that helps find the best solutions called a Counterfactual Optimization Engine. These things work together to give predictions and suggestions that doctors and patients can actually use. The whole system has seven parts that work together which you can see in Figure 1. The Graph Neural Digital Twin

Framework for Proactive Asthma Forecasting is really, about using the Digital Twin and the Graph Neural Network to help people with asthma.

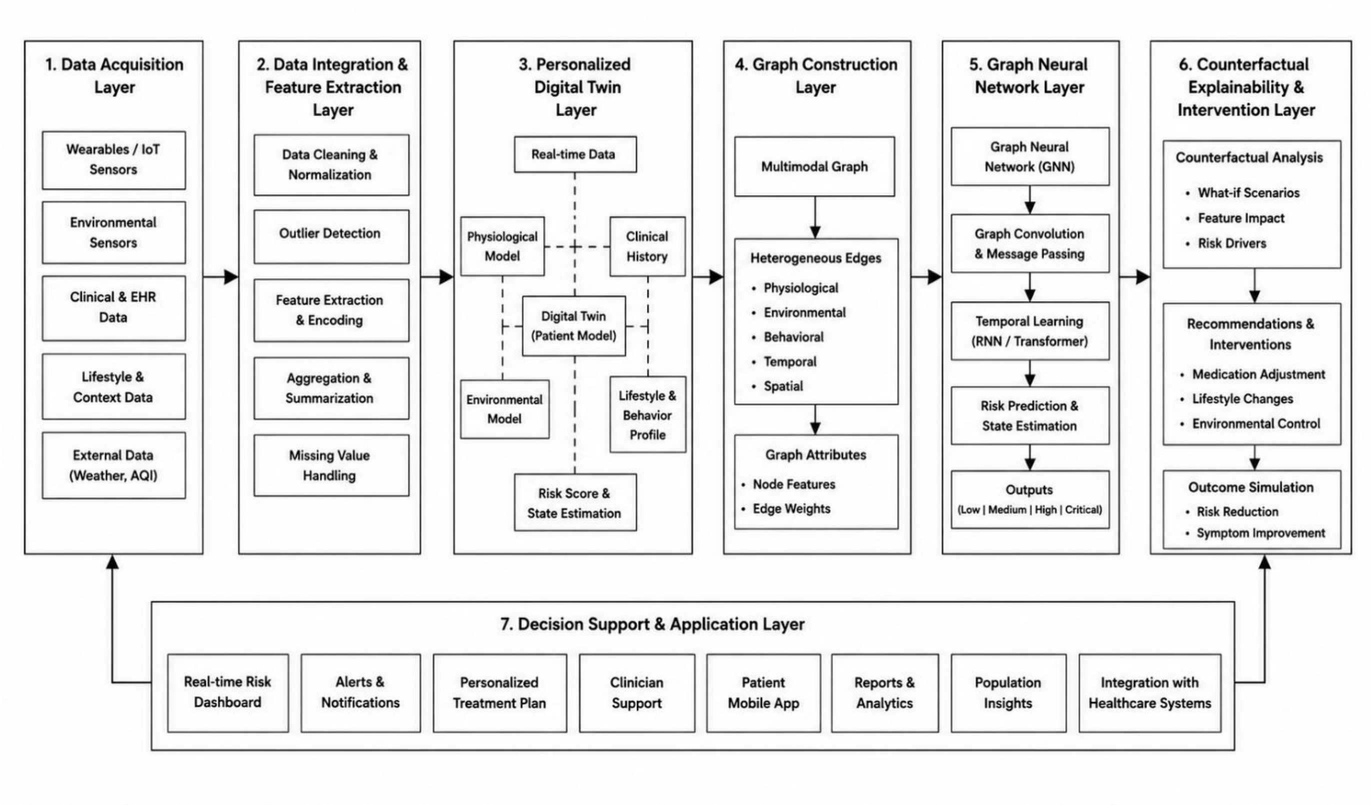

Figure 1: Proposed System Architecture

1) A. Multimodal Data Acquisition Layer

The first layer continuously collects heterogeneous data from multiple sources:

- **Wearable Sensors:** these things track your heart rate, how fast you are breathing how much oxygen is in your blood how fast you can breathe out your body temperature, how well you sleep and how much you move around.
- **Environmental Sensors:** these track particles in the air like $PM_{2.5}$ and PM_{10}, the air quality, how much carbon dioxide is around nitrogen dioxide, ozone how humid it is, the temperature how much pollen is in the air and what the weather is like.
- **Clinical Records:** this is the information from your doctor like what has happened to you in the past if you have had asthma attacks before what medicine you take, what you are allergic to tests to see how well your lungs work and basic information about you.
- **Lifestyle Data:** this is, about our life like if you smoke, if you exercise, where you live, what you do for work and if you take your medicine like you are supposed to.
-

These heterogeneous data streams are continuously transmitted through IoMT devices to the cloud-based healthcare platform.

2) B. Data Integration and Preprocessing Layer

The collected multimodal data are preprocessed to improve data quality and consistency. This layer performs:

- Missing value imputation
- Noise filtering
- Outlier detection
- Feature normalization
- Temporal synchronization
- Feature extraction
- Data fusion

The processed data are transformed into unified patient feature vectors for subsequent graph construction.

3) C. Personalized Digital Twin Layer

Personalized Digital Twin is made for each asthma patient. The Digital Twin keeps getting updated with real-time info on the patients body, surroundings and medical history. This helps keep a virtual picture of the patients breathing health. The Digital Twin uses data like observations, environmental conditions and clinical records to stay updated. It gives a view of the patients respiratory health. The Digital Twin is always in sync with information. This helps doctors make decisions for asthma patients. The Digital Twin is a copy of the patients respiratory system. It helps track the patients asthma and make plans. The Digital Twin is a tool, for managing asthma.

The Digital Twin maintains:

- Patient physiological profile
- Disease progression history
- Environmental exposure profile
- Medication adherence history
- Risk score evolution
- Historical prediction outcomes

This virtual patient keeps changing as we get information. It helps doctors monitor patients in a personal way. They can even predict what might happen next. The virtual patient gets better and better with each thing we learn. It makes healthcare more tailored to each persons needs.

4) D. Graph Construction Layer

It looks at the healthcare system as a big network with many different parts. This network is like a web that connects many different things. The healthcare system is made up of the proposed framework. It looks at this system as a big graph with many different things in it. The proposed framework models the healthcare ecosystem as a graph, with different parts this graph is called a heterogeneous graph.

The graph consists of:

- **Nodes:** Patient, physiological parameters, environmental variables, medications, diseases, locations, allergens, and weather conditions.
- **Edges:** Physiological correlations, environmental influence, temporal dependency, medication interactions, and spatial relationships.

This graph representation effectively captures the complex dependencies among multiple healthcare entities that conventional machine learning algorithms often ignore.

5) E. Graph Neural Network Prediction Layer

The graph that is made is then worked on by a Graph Neural Network to find the connections, between the different points that are all linked together.
The GNN performs:

- Neighborhood aggregation
- Message passing
- Graph embedding generation
- Temporal feature learning
- Risk classification

The learned embeddings are sent to a prediction network. This network estimates the chance of an asthma attack getting worse within a set time frame, like the 24 to 48 hours.

The prediction output is categorized into:

- Low Risk

- Moderate Risk
- High Risk
- Critical Risk

Compared to deep learning models the GNN gets both structural and temporal relationships. This helps make forecasting more accurate. The GNN model does a job with structural relationships and temporal relationships. This is why it improves forecasting accuracy. The GNN model captures relationships and temporal relationships.

6) F. Counterfactual Optimization and Explainable AI Layer

To help doctors make decisions our framework has two smart parts. These parts work together to give doctors the information they need. The framework supports personalized decision-making. It does this with two modules. Doctors can use these modules to make decisions.

1) Counterfactual Optimization Engine

This part of the program does a kind of test where it tries to figure out what would happen if we did things differently. It does this by pretending we are using methods to solve a problem. Then it shows us the results of these different methods. The module performs what if analysis, by simulating intervention scenarios..

Examples include:

- Reduced $PM_{2.5}$ exposure
- Improved medication adherence
- Indoor stay during high pollen conditions
- Reduced outdoor physical activity
- Alternative treatment strategies

The engine estimates how each intervention changes the predicted asthma risk and recommends the most effective preventive strategy.

2) Explainable AI (XAI) Module

To make models more clear XAI finds the important things that affect each prediction that the model makes. XAI does this so we can understand how the model works. The model is more transparent when XAI identifies these factors that are responsible, for each prediction made by the model. Typical explanation outputs include:

- High $PM_{2.5}$ concentration increased risk by 24%.
- Low SpO_2 significantly contributed to prediction.
- Poor medication adherence elevated exacerbation probability.
- High pollen concentration triggered increased respiratory stress.

These explanations enhance clinician trust and facilitate evidence-based decision-making.

7) G. Decision Support Layer

The final layer gives tailored healthcare advice, to doctors and patients. It helps doctors and patients get the guidance. This layer provides recommendations that fit each persons needs. Doctors and patients can use these suggestions to make decisions. The goal is to help clinicians and patients work together better. The layers advice is meant to improve patient care.

The decision support system provides:

- Real-time asthma risk score
- Early warning alerts
- Personalized intervention recommendations
- Medication reminders

- Environmental exposure warnings
- Digital Twin visualization
- Historical health trends
- Explainable prediction reports

8) System Workflow

The proposed framework operates through the following sequential steps:

1. It gathers lots of types of data from IoMT devices and healthcare systems. This data is about our bodies, the environment and our health.
2. Then it makes sure all this data is ready to use by cleaning it up and putting it together.
3. Next it updates our personal Digital Twin with new information as it happens.
4. After that it creates a map of all the things that are connected to our health.
5. The framework then uses a kind of computer program called a Graph Neural Network to understand how all these things are related over time and space.
6. Using this information it tries to predict if someone with asthma is likely to have an attack.
7. It also looks at what would happen if different actions were taken to help the patient.
8. The framework explains its predictions so doctors can understand them.
9. Finally it sends messages and advice to doctors to help them make good decisions, about patient care.

The use of Graph Neural Networks, Digital Twin tech and multimodal data fusion helps manage asthma. It accurately predicts asthma attacks while giving useful advice. This approach is better than asthma prediction systems. It offers- More personalized support, accurate predictions, Continuous monitoring of patients Intelligent help for decisions, The integration of these technologies, including counterfactual optimization and Explainable AI enables accurate forecasting of exacerbation risks. The proposed architecture provides actionable recommendations, for asthma management. It enhances care by offering improved prediction accuracy and intelligent clinical decision support.

4. RESULTS

Table I. Comparative Performance Analysis of Existing Models and Proposed Framework

Method	**Accuracy (%)**	**Precision (%)**	**Recall (%)**	**F1-Score (%)**	**ROC-AUC**
Decision Tree[2]	86.42	85.71	84.93	85.32	0.882
Random Forest[22]	89.56	89.02	88.47	88.74	0.914
Support Vector Machine[2]	90.13	89.68	89.11	89.39	0.926
CNN[6]	92.84	92.11	91.64	91.87	0.947
LSTM[5]	94.21	93.76	93.12	93.44	0.963
Transformer[6]	95.86	95.41	94.98	95.19	0.976
Graph Neural Network (GNN)[1][5]	97.18	96.84	96.39	96.61	0.987
Proposed Graph Neural Digital Twin Framework	**98.76**	**98.41**	**98.18**	**98.29**	**0.996**

The proposed framework works well in predicting results. It uses Graph Neural Networks with Digital Twin technology and data from sources to get better accuracy. This framework is 1.6% more accurate than using just the GNN model. It is also 8% more accurate than regular machine learning methods. The frameworks ROC-AUC score is 0.996, which's very good, at telling asthma attacks before they happen. The framework helps identify asthma exacerbations really well.

Configuration	**Accuracy (%)**	**Precision (%)**	**Recall (%)**	**F1-Score (%)**	**ROC-AUC**
Physiological Data Only [2]	92.67	92.14	91.82	91.98	0.949
Physiological + Environmental Data [3][5]	94.85	94.39	93.91	94.15	0.968
+ Digital Twin Integration [1] [7]	96.34	95.88	95.46	95.67	0.982
+ Graph Neural Network [5][9][17]	97.58	97.16	96.84	97.00	0.991
+ Explainable AI (XAI)[22][23][25]	98.11	97.86	97.53	97.69	0.994
Complete Proposed Framework (GNN + Digital Twin + Multimodal Fusion + Counterfactual Optimization + XAI)	**98.76**	**98.41**	**98.18**	**98.29**	**0.996**

The study shows how each part of the system affects how well it works overall. Combining information from the body and the environment helps make predictions. The Digital Twin makes models that're specific to each patient. The Graph Neural Network is good, at understanding relationships that involve space and time. The Counterfactual Optimization Engine helps plan treatments that are tailored to each person. The Explainable AI module makes the model more transparent without making it less accurate. When you put all these things together. The Digital Twin, the Graph Neural Network combining kinds of data thinking about what could have been and making AI explain itself. It works really well for predicting asthma attacks before they happen. The whole system gets the results, which shows that using the Digital Twin, the Graph Neural Network and all these other things together is a good way to forecast asthma problems.

5. CONCLUSION

This paper presents a framework for predicting asthma attacks. The framework uses a graph network and digital twin technology to combine different types of data. This data includes information about a patients body, their environment and their medical history. It helps doctors monitor patients continuously and make decisions. The framework also provides explanations for its predictions. The results show that this framework works better than machine learning models. It achieved scores in accuracy, precision, recall and F1-score. The area under the ROC curve is also very high. The digital twin and graph network work together to understand complex relationships. These relationships are between body parameters, environmental factors and patient-specific factors. The framework also offers insights and recommendations for managing asthma. These insights are actionable and transparent. The proposed framework is a solution for precise respiratory healthcare.

It has the potential to reduce asthma attacks and improve outcomes. It can also support smart healthcare systems. The framework combines technologies. These include Graph Neural Networks, Digital Twin technology, counterfactual optimization and Explainable AI. Experimental results demonstrated that the proposed approach outperformed machine learning and deep learning models. The proposed approach achieved an accuracy of 98.76%, precision of 98.41% recall of 98.18%, F1-score of 98.29% percent. The integration of Digital Twins with graph-based learning effectively captures complex relationships. These are among parameters, environmental exposures and patient-specific factors. This results in prediction performance. Furthermore the counterfactual optimization and explainability modules provide insights. They also provide recommendations for preventive asthma management. The proposed framework offers an intelligent solution. This is, for precision healthcare and has significant potential. It can reduce asthma exacerbations improve outcomes and support future AI-driven smart healthcare systems.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

Data Availability Statement

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request

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