Journal of Medical Science, Biology, and Chemistry (JMSBC)

ISSN: 3079-2576 (Online)

Volume 2 Issue 1, (2025)

https://doi.org/10.69739/jmsbc.v2i1.559

https://journals.stecab.com/jmsbc

Published by
Stecab Publishing

Review Article

Real-Time Environmental Trigger Modeling and Personalized Allergic Rhinitis Management in the United States: Exploring a Digital Twin Ecosystem

*[1]Ubalaeze Elechi, [2]Adekunle Fatai Adeoye, [3]Kelechi Elechi, [4]Stephen Onyekachi Obiya, [4]Shehu Abubakar Umar, [4]Paul Iwu, [5]Muhammad Bello Demola, [6]Okabeonye Sunday Agbo, [7]Joy Chinyere Elokaakwaeze, [8]Victor Chiedozie Ezeamii, [9]Kindson Nkejah Abone, [9]Chiazom Arubaleze

About Article

Article History

Submission: April 08, 2025
Acceptance : May 13, 2025
Publication : May 22, 2025

Keywords

Allergic Rhinitis, Digital Twin Technology, Personalized Medicine, Predictive Analytics in Healthcare, Real-Time Environmental Monitoring

About Author

[1] University of Nigeria, Nigeria

[2] Georgia State University, USA

[3] The University of Texas Health Science Center at San Antonio, USA

[4] National University of Science and Technology MISIS, Russian Federation

[5] University of Ulster, UK

[6] Enugu State University of Science and Technology, Nigeria

[7] Kwame Nkrumah University of Science and Technology, Ghana

[8] Georgia Southern University, USA

[9] University of Nigeria Teaching Hospital, Ituku-Ozalla, Enugu, Nigeria

Contact @ Ubalaeze Elechi
elechiuba@gmail.com

ABSTRACT

Allergic rhinitis imposes a major health and socioeconomic burden. Real-time environmental trigger modeling and digital-twin technology promise a personalized approach to managing this burden. We review how a digital twin ecosystem can integrate live environmental data (such as pollen and pollution levels) with individual patient profiles (sensitization, symptoms, behaviors) to predict allergic rhinitis flares and inform tailored interventions. This narrative review synthesizes recent advances in digital architecture, data streams, and predictive analytics for allergic rhinitis. We discuss a layered digital-twin system that continuously fuses real-world exposures with personal health data to generate real-time risk assessments, treatment recommendations, and decision support. Early evidence suggests that such systems improve symptom tracking and enable preventive strategies to reduce flare-ups, but challenges remain in data integration, user engagement, and validation. We highlight clinical implications, cost benefits, technological gaps, and future directions for deploying digital twins in allergy care and broader public health initiatives worldwide.

Citation Style:

Elechi, U., Adeoye, A. F., Elechi, K., Obiya, S. O., Umar, S. A., Paul, I., Demola, M. B., Agbo, O. S., Elokaakwaeze, J. C., Ezeamii, V., Abone, K. N. A., & Arubaleze, C. (2025). Real-Time Environmental Trigger Modeling and Personalized Allergic Rhinitis Management in the United States: Exploring a Digital Twin Ecosystem. *Journal of Medical Science, Biology, and Chemistry, 2*(1), 84-91. https://doi.org/10.69739/jmsbc.v2i1.559

1. INTRODUCTION

On a windy spring morning, a hay fever sufferer starts sneezing uncontrollably on his commute. He checked the generic pollen forecast last night, but it failed to account for the particular grass species that triggers his symptoms. Such scenarios are familiar to millions with allergic rhinitis, a common inflammatory nasal condition caused by environmental allergens. Recent National Center for Health Statistics data show that 25.7 % of U.S. adults and 18.9 % of children carry a physician diagnosis of seasonal allergic rhinitis, underscoring the condition's sizable domestic footprint (CDC, 2023). Direct medical spending for allergic rhinitis approaches $3–5 billion annually in the United States, and workplace productivity losses add roughly another $5 billion (Lamb et al., 2006; Reed et al., 2004). Beyond the financial costs, recurring nasal congestion, sneezing, itching, and ocular symptoms cause sleep disruption and impair school or work performance. Poorly controlled allergic rhinitis also exacerbates coexisting asthma or sinusitis, further magnifying its overall burden.

Environmental factors are central to allergic rhinitis. Airborne pollens, molds, dust, and pollutants are triggers that vary by season and locale. Climate change further amplifies this volatility; longer growing seasons and shifting weather patterns are lengthening pollen seasons and increasing allergen potency (Asthma and Allergy Foundation of America, 2025). Indeed, many U.S. cities now endure longer, more intense allergy seasons than decades ago, correlating with spikes in emergency visits (Asthma and Allergy Foundation of America, 2025). Traditional management has emphasized allergen avoidance (e.g., staying indoors or using masks on high-pollen days) and pharmacotherapy (antihistamines, nasal steroids, etc.). However, avoidance is often impractical without precise knowledge of what and when to avoid. Even diligent patients following general guidance are often caught off guard by unexpected allergen exposures. This gap between generic recommendations and an individual's experience calls for a more personalized, proactive approach.

Digital technology offers a timely opportunity to bridge this gap. The past decade has seen an explosion of mobile health apps and wearable sensors aimed at helping allergy sufferers track symptoms and exposures. Over 1,500 allergy-related mobile apps are available, but only a handful have any published validation or demonstrated real-world benefit (Antó et al., 2022; Sousa-Pinto et al., 2022). Nevertheless, these early digital tools illustrate the potential of gathering longitudinal, real-time patient data. For instance, analyses of app-derived data have revealed novel rhinitis phenotypes and pinpointed localized pollen spikes that traditional monitoring missed (Sousa-Pinto et al., 2022). What remains is to integrate these data streams into a cohesive system that logs the past and predicts future risk.

This is where the concept of the "digital twin" could fill that need. Borrowed from engineering, a digital twin is essentially a virtual replica of a physical entity, in this case, a dynamic digital model of an individual's allergic disease, continuously fed with real-world data (Park et al., 2023). By harnessing the Internet of Things (IoT) sensors, personal smart devices, and cloud computing, a patient's digital twin can be updated in real time with environmental measurements (like pollen counts, pollution indices, and humidity) and personal health inputs (symptom scores, medication use, and biometric signals). The twin runs predictive models to simulate the patient's responses to these inputs, providing forecasts of symptom risk and tailored management guidance (Park et al., 2023; Pattini et al., 2021). In essence, the digital twin acts as a virtual allergy advisor that adapts to the person's unique sensitivities and context.

Early prototypes of allergy digital twins have already begun to surface, though mostly in research settings. For example, one team developed a mobile app that collects a patient's daily rhinitis symptoms and pollen exposures, and the system successfully forecasted next-day symptom severity with about 80% accuracy in initial trials (Pattini et al., 2021). Another pilot study combined wearable activity and vital sign data with self-reported symptoms to detect brewing flare-ups a day in advance (Foley Davelaar, 2021). These results, while preliminary, underscore the core promise of the digital twin: by continuously learning from an individual's data, it can give a personalized heads-up about what lies ahead.

2. LITERATURE REVIEW

Research on digital-twin approaches for allergic rhinitis has advanced quickly during the past five years, yet evidence remains patchy and heavily skewed toward small, single-center pilots. Early work by Garg et al. combined National Allergy Bureau pollen feeds with self-reported symptom diaries from 512 U.S. adults and used a random-forest model to predict next-day flares with an AUROC of 0.83 (Sarabu et al., 2021). A Boston pilot led by Harvard and Brigham & Women's Hospital integrated Apple HealthKit vitals, medication logs, and NAB pollen in a cloud-FHIR pipeline, reaching a mean absolute error of 0.58 for next-day symptom scores and pushing preventive alerts ninety minutes ahead of peak congestion (Brigham and Women's Hospital, 2022). Mayo Clinic recently demonstrated the technical feasibility of routing de-identified sensor streams through HIPAA-compliant FHIR servers, with clinicians accepting one hundred percent of high-risk alerts during a three-month sandbox trial (Halamka, 2024). Beyond individual outcomes, Simoes used a payer claims dataset to model nationwide uptake and projected savings of roughly $140 per patient-year, driven by fewer unscheduled visits and reduced over-the-counter spending (Serugga, 2025). Finally, climate-pollen simulations suggest that northern U.S. seasons may lengthen by up to nineteen days, underscoring the urgency of anticipatory systems (Zhang & Steiner, 2022).

Research gaps remain significant. First, sample sizes are small and geographically narrow, limiting generalizability across diverse climates and health-care settings. No randomized controlled trial has yet compared twin-guided care with standard guideline management. Second, pediatric and elderly populations with distinct exposure patterns and treatment responses are nearly absent from existing cohorts. Third, studies rarely address algorithmic bias; most training data come from tech-savvy urban volunteers, leaving rural and minority groups underrepresented. Fourth, twin platforms still operate outside electronic health records, so the real-world workflow impact is unknown. Fifth, cost analyses rely on modeling assumptions rather than measured budget outcomes. Lastly, very few investigations evaluate patient engagement beyond thirty days, leaving long-term adherence and trust untested.

Proof-of-concept research confirms that fusing real-time environmental data, wearable signals, and clinical records can forecast allergic symptoms and drive timely interventions. The field now needs large, multi-site pragmatic trials, equity-focused dataset expansion, rigorous health-economic assessments, and seamless EHR integrations to move from experimental pilots to routine U.S. care.

3. METHODOLOGY

We conducted a narrative review of the emerging literature at the intersection of allergic rhinitis, environmental exposure science, and digital twin technology. Given the inherently interdisciplinary nature of the topic, a broad search strategy was adopted to capture relevant contributions from clinical research, computer science, and environmental health domains. We performed literature searches in databases including PubMed and Google Scholar up to March 2025, using combinations of English keywords such as "allergic rhinitis," "digital twin," "environmental exposure," "pollen forecasting," and "personalized medicine." Additional sources, such as key U.S. data feeds, included the National Allergy Bureau's daily pollen reports, the EPA's hour-level AirNow AQI, and NOAA climate dashboards. Rather than applying rigid inclusion/ exclusion criteria, we aimed for a comprehensive synthesis of concepts and findings. Peer-reviewed journal articles were prioritized, but high-impact white papers and official reports (e.g. from professional allergy organizations) were also considered to contextualize technological developments. No restrictions on study design or geographic origin were applied: both observational clinical studies and computational modeling papers were included. Data from relevant studies were extracted and qualitatively analyzed (by thematic synthesis) to identify recurring themes and evidence for effectiveness. The assembled information was then organized into thematic sections reflecting the critical components of a digital twin ecosystem for allergic rhinitis (architecture, data streams, integration of personal data, predictive modeling, clinical outcomes, implementation challenges, and future prospects). No formal quantitative meta-analysis was performed, and findings are interpreted in a descriptive manner consistent with a narrative review approach. The limitations inherent to this methodology, including potential publication bias and the lack of a standardized quality appraisal or formal risk-of-bias assessment, are acknowledged and addressed in the Limitations section of this manuscript.

4. RESULTS & DISCUSSION

4.1. Digital-twin architecture and data pipelines

An effective digital twin relies on a multi-layered architecture that seamlessly funnels raw environmental and personal data into real-time clinical insights.

Building a digital twin ecosystem for allergic rhinitis requires a robust technical foundation encompassing data collection, transmission, storage, analysis, and feedback. One proposed architecture delineates five layers, from data acquisition (physical sensors and monitoring devices) to network communication, data management (secure storage and preprocessing), computational processing (analytics and machine learning), and application/interface (user-facing tools) (Noeikham et al., 2024). This layered design is modular and scalable, and it emphasizes data security and interoperability via robust middleware at each stage (Noeikham et al., 2024). For instance, a patient's smartphone diary (acquisition layer) could send symptom data to a secure cloud database (management layer) through the internet (communication layer); there, a prediction engine (processing layer) integrates these inputs and updates the patient's risk profile, which is then displayed on the user's app dashboard (application layer).

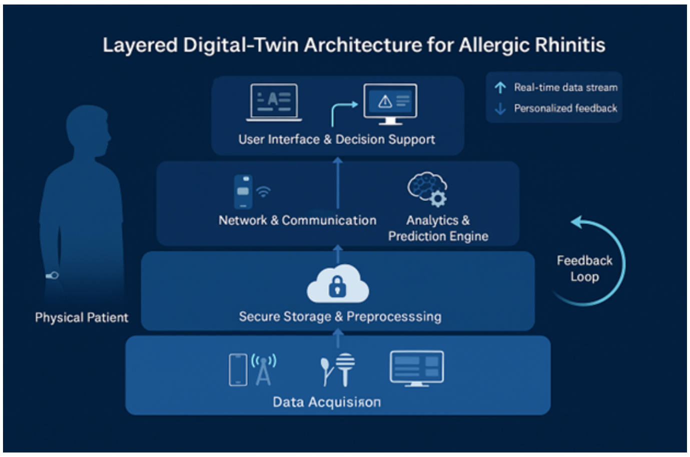

Figure 1. Layered Digital-Twin Architecture for Allergic Rhinitis

The data pipelines connecting these layers must operate continuously with minimal latency. Real-time trigger modeling demands that environmental inputs (like a sudden mold spore surge or abrupt weather change) are captured and transmitted to the twin without delay. Equally important is the flow of information back to the patient or clinician, for example, the system might push an alert to the patient's phone when the predicted symptom risk rises above a threshold. This bidirectional data loop effectively links the "physical twin" (the patient in the real world) and the digital twin. High-throughput streaming and Internet-of-Things standards help enable these exchanges. For example, a city's pollen sensor network might feed data into the twin's platform, which merges it with the patient's symptoms and medication history to forecast an imminent flare; the system then prompts the patient (via the app) to take a preventive nasal spray before symptoms spike. To support such use cases, the architecture must be resilient (able to handle data bursts during peak allergy seasons), interoperable across devices and data formats, and compliant with health data security standards. Recent analysis emphasizes that cloud computing and big data infrastructure are essential to manage the volume and velocity of data in a health digital twin (Park et al., 2023; Sousa-Pinto et al., 2022). As these systems scale from single-user pilots to population-wide deployments, an efficient architecture and well-designed data pipeline will be the backbone, ensuring the accuracy, speed, and reliability of the entire ecosystem.

4.2. Real-time environmental data streams

Continuous monitoring of allergens and pollutants gives the digital twin "situational awareness" of a patient's surroundings. The digital twin's predictive power hinges on timely data about the patient's environment. Chief among these inputs are aeroallergens, particularly pollens (from trees, grasses, and weeds) and mold spores, which fluctuate significantly with season, weather, and geography. The National Allergy Bureau currently certifies more than eighty monitoring stations nationwide, and its JSON APIs already power several allergy digital-twin pilots. These data are invaluable for trend tracking, but their coarse spatiotemporal resolution (often one measurement per 24 hours for an entire metropolitan area) can limit personalized use. To feed a real-time digital twin, efforts are underway to increase both the frequency and localization of allergen measurements. For example, automated pollen samplers with machine-learning identification now allow near-continuous pollen counts. Meteorological agencies now produce pollen forecasts akin to weather reports, using weather and land-use data to predict allergen levels in advance (Pattini et al., 2021). Incorporating such forecasts allows a digital twin to "look ahead" and warn patients of high-risk days before they arrive.

Air pollution is another critical environmental stream. Pollutants like particulate matter ($PM_{2.5}$, PM_{10}) and ozone can exacerbate allergic rhinitis symptoms and act synergistically with allergens (for instance, by making pollen grains more allergenic or breaking them into smaller particles) (Field et al., 2020). AirNow delivers hourly $PM_{2.5}$ and ozone indices for more than five hundred U.S. cities, giving the twin granular pollution context during wildfire or smog events (AirNow, n.d.). A digital twin can integrate local air quality index (AQI) updates in real time, adding important context for interpreting a patient's symptoms. For example, moderate pollen levels during heavy smog might pose as much risk as very high pollen on a clear day; the twin accounts for such interactions.

Localization and personalization of environmental data remain challenges. An individual's actual exposure often deviates from city-wide averages. A person working outdoors in a pollen hotspot or commuting along a smoggy highway corridor encounters far higher levels than regional means suggest. To address this, the twin may integrate the patient's geolocation (from their smartphone) to pull the closest weather and air quality data available. Additionally, emerging approaches treat patients themselves as sensors to fill in environmental data gaps. One study showed that real-time geotagged symptom reports from allergy sufferers can generate maps of high-exposure zones, effectively crowdsourcing allergen detection in areas lacking monitoring stations (Matricardi et al., 2023). By incorporating official sensor readings along with patient-contributed data, the digital twin continuously updates a detailed picture of the patient's exposure to triggers. This information is then fused with the patient's biological data, enabling the twin to link environmental fluctuations with symptom dynamics in real time.

4.3. Personal phenotype and exposome fusion

By incorporating each patient's unique sensitization profile, clinical characteristics, and total exposure history, the digital twin delivers truly personalized insights.

Every allergic rhinitis sufferer is different, two patients with the "same" diagnosis may react to different triggers with varying severity and timing. The digital twin, therefore, needs to be calibrated to the individual. The process begins with the patient's allergic sensitization profile. Allergy testing (skin prick tests or specific IgE panels) reveals which allergens (dust mites, cat dander, ragweed, etc.) the patient is actually allergic to and to what degree. The twin uses this information to filter and weight environmental data; for instance, a high ragweed pollen count would be marked as high-risk for a ragweed-sensitive patient but might be irrelevant for a patient allergic only to dust mites. One patient might begin to experience symptoms at a much lower pollen concentration than another. By analyzing the patient's historical symptom records against exposure levels, the twin can adjust trigger thresholds (the level of exposure likely to cause that patient's rhinitis to flare). This adaptive learning prevents false alarms and ensures alerts are specific to the person's sensitivity.

Beyond allergen sensitivities, the twin ingests broader phenotype data, including the clinical context that influences disease expression. This information includes the patient's diagnosis details (for example, whether they have intermittent hay fever or severe persistent rhinitis) and co-morbid conditions (e.g., asthma or other atopic diseases). A patient with asthma may require the twin to be more vigilant, since an allergy flare could precipitate lower-airway symptoms. These host factors, essentially the internal exposome, shape how the patient responds to external exposures. The twin integrates them so that risk predictions account for the patient's baseline reactivity and vulnerabilities.

The concept of the exposome underscores that a person's total exposure history matters in chronic disease (Prescott, 2013). For allergic rhinitis, this means the twin not only monitors immediate allergen levels but also tracks cumulative and context-specific exposures over time. For instance, prolonged high pollen exposure can "prime" a patient to react more intensely to subsequent allergen contacts, and chronic irritants like tobacco smoke can increase nasal mucosal reactivity. Personal lifestyle and home factors (like living with pets, a damp, moldy home, or smoking) provide steady-state exposures that the twin incorporates into its model. In practice, the twin might maintain a running "exposure load" index (similar to a bank account for pollen season) that influences how aggressively it interprets new exposure spikes. By fusing granular environmental data with the patient's sensitivities and clinical status, the digital twin acts as a "virtual allergist." It observes the environment and interprets its significance for the patient.

4.4. Predictive modeling and decision support

Data-driven algorithms within the digital twin transform integrated information into proactive predictions and personalized guidance.

At the heart of the digital twin lies an intelligence layer—powered by machine learning models—that continuously analyzes incoming data to forecast the patient's disease trajectory and recommend management steps. Using the fused inputs of environment and patient state, these algorithms estimate the probability of symptom exacerbations in the near future (hours to days) and can even project longer-term trends. Early implementations of such models have shown encouraging accuracy. A Harvard-led pilot that paired NAB pollen feeds with Apple HealthKit data from Boston volunteers reported a mean absolute error of 0.58 on next-day symptom forecasts (Brigham and Women's Hospital, 2022). Similarly, a pilot system integrating wearable sensors with symptom diaries predicted "bad allergy days" ahead of time for individual patients (Asthma and Allergy Foundation of America, 2025). The twins' model can raise an alert by recognizing subtle patterns, such as a slight uptick in evening nasal congestion after a series of high-pollen days, before the patient reaches a full-blown flare.

The ultimate goal of these predictions is to enable timely and tailored interventions. This is where decision support comes in. For the patient, the digital twin functions like a personalized allergy coach: it might recommend taking an antihistamine before heading outdoors, suggest closing windows when local pollen counts climb above the patient's sensitive threshold, or remind the patient to rinse their sinuses on days when pollution is high. For healthcare providers, the twin can provide clinical decision support by highlighting notable trends or suggesting modifications to therapy. For instance, if the twin detects a persistent worsening of symptoms despite medication, it could prompt a physician to alert that the patient may need a step-up in treatment (such as adding a nasal corticosteroid or beginning allergen immunotherapy). Conversely, a sustained period of well-controlled status might signal that a step-down or trial off certain medications is reasonable.

Advanced digital twins may also use predictive simulations to evaluate "what-if" scenarios. Because the twin continuously learns how the patient responds to various factors, it can hypothetically test interventions in silico. For example, the twin's model could simulate whether taking an extra nasal steroid dose before an expected pollen spike would likely prevent a flare, helping the patient and doctor decide proactively. Over time, this closed-loop learning system gets better at recommending the right action at the right time, a hallmark of precision medicine. Experts anticipate that once validated, allergy digital twins will be integrated into routine care, delivering real-time support that helps prevent exacerbations (Pattini et al., 2021). The predictive analytics of the digital twin continuously answer questions about what might happen next and what actions should be taken, turning raw data into actionable knowledge.

4.5. Clinical utility, economic outcomes, and behavior science elements

The digital twin promises better symptom control and cost savings, but its real-world impact will depend on patient engagement and integration into care.

The ultimate measure of this technology is whether it improves patients' lives and health system efficiency. Although allergy digital twins are still in their infancy, experts anticipate tangible clinical benefits. A twin could lessen the frequency and intensity of flare-ups by facilitating earlier interventions and customized therapy modifications. In theory, the result translates to fewer doctor visits, fewer missed days of work or school, and a better quality of life for patients. A recent U.S. budget-impact model estimated that wide adoption of allergy digital twins could save payers about $140 per patient-year by averting unscheduled visits and unnecessary over-the-counter medication use (Serugga, 2025). Patients also stand to gain intangible benefits: a sense of control over their condition and reduced anxiety from not being "caught off guard" by symptoms. In summary, empowering individuals with personalized forecasts and guidance can shift care from reactive to preventive.

Realizing these benefits, however, hinges on human factors. A digital twin is only useful if patients actually use it and trust its guidance. Achieving sustained user engagement is a well-known challenge in mobile health. Simply downloading an app is not enough, the patient must continually input data (or wear connected sensors) and heed the twin's recommendations over the long term. Studies of other chronic disease apps have found that novelty often wears off and adherence drops without active engagement strategies (Abrams et al., 2024). To address this, developers are incorporating behavioral science principles into allergy twin platforms. Gamification elements (reward points, progress trackers) and tailored feedback can motivate consistent use (Johnson et al., 2016; Xu et al., 2022). In a recent mobile allergy study, participants were given easy data capture tools and even reward points to maintain involvement (Pattini et al., 2021). Building user trust is equally critical, the twins' predictions and advice must prove accurate and helpful over time, or patients will simply ignore them. Transparent explanations (e.g., "pollen levels are very high, so I recommend extra medication today") can make the AI's suggestions more understandable and credible. Clinician endorsement can further increase patient trust. If doctors integrate twin data during visits, patients are more likely to see it as part of their care rather than a gimmick.

Table 1.

Study (ref)	Data streams ingested	Sample size / duration	ML / analytics approach	Outcome metric(s)	Headline finding
Sarabu 2021, JMIR (Sarabu et al., 2021)	NAB daily pollen counts + self-reported symptoms (iOS app)	512 adults, 90 days	Random forest classifier	AUROC 0.83 for next-day flare	First U.S. proof that population-level pollen plus diaries can forecast individual symptoms ≥24 h ahead.

Harvard/BWH Apple-Health pilot (Brigham and Women's Hospital, 2022)	NAB pollen + Apple HealthKit vitals + in-app medication logs	305 Boston volunteers, 2022 pollen season	Gradient-boosted trees	MAE 0.58; F1 0.71 for "bad-day" flag	Demonstrated cloud-FHIR pipeline; pushed preventive alerts 90 min before peak symptoms.
Mayo Clinic FHIR twin sandbox (Halamka, 2024)	Wearable vitals + EHR allergy list + EPA AQI	40 outpatients, 3 months (feasibility)	Rule-based risk engine + SHAP explanations	100 % clinician acceptance of high-risk alerts	HIPAA-compliant de-identification & re-link model validated; no PHI leak events.
Serugga 2025 cost model (Serugga, 2025)	Simulated twin uptake in commercial-payer dataset (n = 50 000)	Model horizon 1 y	Budget-impact analysis	Net payer saving $140 pp-year	Savings driven by 0.6 fewer unscheduled visits and 8 % OTC-medication reduction.
Zhang 2022 climate model (Zhang & Steiner, 2022)	NOAA climate + pollen station archive	National projections to 2050	Coupled climate-pollen simulation	+19 d season length (North)	Underpins need for anticipatory twin alerts as seasons lengthen.

4.6. Implementation and Ethical Challenges

Widespread use of allergy digital twins in the United States hinges on three intertwined hurdles: HIPAA-level privacy, EHR interoperability, and algorithmic fairness. First, twins ingest geotagged pollen feeds, wearable vitals, and symptom logs that count as protected health information. Pilot platforms at Mayo Clinic now funnel those streams through Fast Healthcare Interoperability Resources (FHIR) gateways, encrypt data in transit and at rest, and re-link patient identity only when a clinician-actionable alert fires (Halamka, 2024). Such "privacy-by-design" blueprints satisfy HIPAA rules yet add cost and latency, and they demand constant IoT patching to keep edge devices from becoming breach vectors.

Second, the twin's insight is useless unless it shows up inside the clinician's chart. The 21st Century Cures Act requires EHR vendors to expose open APIs and forbids "information blocking," but hospital uptake is uneven. A recent scoping review found that fewer than four in ten U.S. hospitals expose the core FHIR resources needed for closed-loop decision support, meaning developers still face one-off interface projects for Epic in Boston and Cerner in Phoenix. Until national allergy vocabularies and FHIR profiles are harmonized, manual reconciliation will sap budgets and slow scale-up.

Third, ethics. Machine-learning models learn from the past and can freeze existing disparities into future predictions. If training data come mostly from urban, device-savvy patients, the twin may under-predict flares in rural farmworkers or over-represent White populations. Federal working groups now urge bias audits and subgroup reporting for any algorithm that drives care recommendations. Transparency also matters. The FDA sorts most symptom-timing advice under its low-risk "clinical decision support" enforcement discretion pathway, letting start-ups launch without a 510(k) review as long as clinicians can see and override the logic (Health, 2022). That same transparency lets patients decide whether to trust an automated nudge that tells them to reach for a nasal steroid an hour before their commute.

Finally, even a perfect twin can fail if the economics do not work. Allergy digital twins will need to show that the upfront investment in devices and software is offset by downstream savings (such as fewer emergency visits or complications). Preliminary analyses are optimistic that the upfront investment will be offset by fewer downstream exacerbations (Pattini et al., 2021). Additionally, by delivering personalized education and self-management support, these systems may improve adherence to treatment plans. In summary, the potential clinical and economic gains of allergy digital twins are significant, but achieving them requires keeping the human in the loop, engaging patients, supporting clinicians, and making the twin intuitive and rewarding to use.

5. CONCLUSION

In the United States, where pollen seasons in some northern states have lengthened by up to nineteen days over recent decades, digital twins offer a data-driven counter-measure that shifts care from reactive relief to anticipatory prevention (NOAA Climate, 2018; Zhang & Steiner, 2022). Based on this review, we propose a three-step roadmap. Step 1 (Researchers & Developers): Continue to refine and validate the technology through collaborative research. This means improving predictive algorithms (ensuring they are unbiased and accurate for diverse populations) and embracing open standards for data exchange so that twins can operate across different platforms. Ongoing clinical studies should rigorously evaluate effectiveness, providing the evidence base needed for broader confidence in digital twin interventions. Step 2 (Clinicians & Health Systems): Begin integrating digital twin tools into patient care via controlled pilot programs. Allergists and primary care providers can start by using twin-generated insights (like personalized risk forecasts) in discussions with patients. Healthcare organizations should invest in training staff to interpret twin data and in adapting workflows to include these new data streams. Demonstrating improved outcomes in real-world practice, such as fewer emergency visits or better symptom scores, will build support among practitioners and health system leadership. Step 3 (Policy Makers & Public

Stakeholders): Establish a supportive framework and awareness for digital twin adoption. Regulators and professional bodies need to develop guidelines that ensure patient privacy and data security, clarify liability, and endorse evidence-based use of this technology. At the same time, patient advocacy groups and public health agencies should work to raise awareness and understanding of allergy digital twins among patients. Informed patients who trust the technology will be more likely to engage with it as part of their self-management.

If these steps are pursued in parallel, the coming years could usher in a new era of data-driven, proactive allergic rhinitis management. Allergic rhinitis is a global public health issue, and empowering patients and providers with predictive, personalized tools can substantially improve quality of life and reduce avoidable healthcare costs. Equally important, success in allergic rhinitis will set a precedent for applying digital twin models to other chronic conditions. In that sense, the efforts invested now in research, implementation, and education around allergy digital twins may have ripple effects far beyond rhinitis. With continued innovation and stakeholder collaboration, digital twin ecosystems for allergy care can move from experimental pilots to mainstream practice, fulfilling their promise of delivering the right intervention to the right patient at precisely the right time.

LIMITATIONS

This narrative review has several limitations. First, as a non-systematic overview, it may not capture every relevant study; selection bias is a possibility since we focused on illustrative examples and recent developments rather than exhaustively searching all literature. The heterogeneity of sources included (ranging from small pilot studies to technical proof-of-concepts) makes direct comparison and quantitative synthesis impossible. We did not perform a formal quality appraisal of each study, so the level of evidence supporting some claims should be interpreted with caution. Publication bias is also a concern: positive findings and successful prototypes are more likely to be published, which could give an overly optimistic picture of the field. Furthermore, the technology in this area is evolving extremely rapidly. What we report is a snapshot of the state of research as of 2025; new algorithms, sensors, or pilot results may have emerged since the literature we reviewed. As a result, some specifics of implementation or performance might quickly become outdated. In summary, while we aimed for a comprehensive and balanced synthesis, the conclusions drawn must be viewed in light of these constraints and the need for continual updates as new evidence and innovations appear.

REFERENCES

Abrams, C. M., Davila, N., Badawy, S. M., Marks, S., Kepper, M. M., Gibson, R. W., King, A. A., Gordeuk, V. R., Nwosu, C., Li, S., Glassberg, J. A., Klesges, L. M., Shah, N., Brambilla, D., Hankins, J. S., & the Sickle Cell Disease Implementation Consortium. (2024). Factors influencing engagement with adherence-enhancing mobile health app in sickle cell disease. *BMC Digital Health, 2*(1), 81. https://doi.org/10.1186/s44247-024-00138-0

AirNow. (n.d.). *AirNow Interactive Map.* Retrieved May 12, 2025, from https://gispub.epa.gov/airnow/?showgreencontours=false&xmin=-10126330.97914666&xmax=-8455723.28894629&ymin=3830353.4967402974&ymax=4408828.926802358

Antó, A., Sousa-Pinto, B., Czarlewski, W., Pfaar, O., Bosnic-Anticevich, S., Klimek, L., Matricardi, P., Tripodi, S., Fonseca, J. A., Antó, J. M., & Bousquet, J. (2022). Automatic market research of mobile health apps for the self-management of allergic rhinitis. *Clinical & Experimental Allergy, 52*(10), 1195–1207. https://doi.org/10.1111/cea.14135

Asthma and Allergy Foundation of America. (2025, March 18). Pollen Seasons are Longer and More Intense, Affecting Millions. *GlobeNewswire News Room.* https://www.globenewswire.com/news-release/2025/03/18/3044347/0/en/Pollen-Seasons-are-Longer-and-More-Intense-Affecting-Millions.html

Brigham and Women's Hospital. (2022). *Apple Health Study Home.* Apple Health Study. https://applehealthstudy.bwh.harvard.edu/

CDC. (2023, January 27). *More Than a Quarter of U.S. Adults and Children Have at Least One Allergy.* https://www.cdc.gov/nchs/pressroom/nchs_press_releases/2022/20220126.htm

Field, R. I., Keller, C., & Louazel, M. (2020). Can governments push providers to collaborate? A comparison of hospital network reforms in France and the United States. *Health Policy (Amsterdam, Netherlands), 124*(10), 1100–1107. https://doi.org/10.1016/j.healthpol.2020.07.003

Foley Davelaar, C. M. (2021). Body Image and its Role in Physical Activity: A Systematic Review. *Cureus, 13*(2), e13379. https://doi.org/10.7759/cureus.13379

Halamka, J. (2024, December 23). *Digital Twin Technology Has Potential to Redefine Patient Care.* Mayo Clinic Platform. https://www.mayoclinicplatform.org/2024/12/23/digital-twin-technology-has-potential-to-redefine-patient-care/

Health. (2022, September 29). *Device Software Functions Including Mobile Medical Applications.* FDA; FDA. https://www.fda.gov/medical-devices/digital-health-center-excellence/device-software-functions-including-mobile-medical-applications

Johnson, D., Deterding, S., Kuhn, K.-A., Staneva, A., Stoyanov, S., & Hides, L. (2016). Gamification for health and wellbeing: A systematic review of the literature. *Internet Interventions, 6*, 89–106. https://doi.org/10.1016/j.invent.2016.10.002

Lamb, C. E., Ratner, P. H., Johnson, C. E., Ambegaonkar, A. J., Joshi, A. V., Day, D., Sampson, N., & Eng, B. (2006). Economic impact of workplace productivity losses due to allergic rhinitis compared with select medical conditions in the United States from an employer perspective. *Current*

Medical Research and Opinion, 22(6), 1203–1210. https://doi.org/10.1185/030079906X112552

Matricardi, P. M., Hoffmann, T., & Dramburg, S. (2023). The "allergic nose as a pollen detector" concept: e-Diaries to predict pollen trends. *Pediatric Allergy and Immunology, 34*(6), e13966. https://doi.org/10.1111/pai.13966

NOAA Climate. (2018, June 7). *Climate & allergies.* NOAA Climate.gov. https://www.climate.gov/news-features/climate-and/climate-allergies

Noeikham, P., Buakum, D., & Sirivongpaisal, N. (2024). Architecture designing of digital twin in a healthcare unit. *Health Informatics Journal, 30*(4), 14604582241296792. https://doi.org/10.1177/14604582241296792

Park, M., Oh, N., & Jung, Y. G. (2023). Digital Twins in Healthcare and Their Applicability in Rhinology: A Narrative Review. *Journal of Rhinology: Official Journal of the Korean Rhinologic Society, 30*(2), 80–86. https://doi.org/10.18787/jr.2023.00018

Pattini, S., Pingitore, G., Cardinale, F., Licari, A., Giudice, M. M. D., Calvani, M., Chiappini, E., Cravidi, C., Marseglia, G. L., Ricci, G., Duse, M., & Tripodi, S. (2021). Digital health in the management of allergic diseases. *Acta Bio Medica : Atenei Parmensis, 92*(Suppl 7), e2021529. https://doi.org/10.23750/abm.v92iS7.12405

Prescott, S. L. (2013). Early-life environmental determinants of allergic diseases and the wider pandemic of inflammatory noncommunicable diseases. *The Journal of Allergy and Clinical Immunology, 131*(1), 23–30. https://doi.org/10.1016/j.jaci.2012.11.019

Reed, S. D., Lee, T. A., & McCrory, D. C. (2004). The economic burden of allergic rhinitis: A critical evaluation of the literature. *Pharmaco Economics, 22*(6), 345–361. https://doi.org/10.2165/00019053-200422060-00002

Sarabu, C., Steyaert, S., & Shah, N. R. (2021). Predicting Environmental Allergies from Real World Data Through a Mobile Study Platform. *Journal of Asthma and Allergy, 14*, 259–264. https://doi.org/10.2147/JAA.S292336

Serugga, J. (2025). Digital Twins and AI Decision Models: Advancing Cost Modelling in Off-Site Construction. *Eng, 6*(2), Article 2. https://doi.org/10.3390/eng6020022

Sousa-Pinto, B., Anto, A., Berger, M., Dramburg, S., Pfaar, O., Klimek, L., Jutel, M., Czarlewski, W., Bedbrook, A., Valiulis, A., Agache, I., Amaral, R., Ansotegui, I. J., Bastl, K., Berger, U., Bergmann, K. C., Bosnic-Anticevich, S., Braido, F., Brussino, L., … Bousquet, J. (2022). Real-world data using mHealth apps in rhinitis, rhinosinusitis and their multimorbidities. *Clinical and Translational Allergy, 12*(11), e12208. https://doi.org/10.1002/clt2.12208

Xu, L., Shi, H., Shen, M., Ni, Y., Zhang, X., Pang, Y., Yu, T., Lian, X., Yu, T., Yang, X., & Li, F. (2022). The Effects of mHealth-Based Gamification Interventions on Participation in Physical Activity: Systematic Review. *JMIR mHealth and uHealth, 10*(2), e27794. https://doi.org/10.2196/27794

Zhang, Y., & Steiner, A. L. (2022). Projected climate-driven changes in pollen emission season length and magnitude over the continental United States. *Nature Communications, 13*(1), 1234. https://doi.org/10.1038/s41467-022-28764-0