© DEC 2025 | IRE Journals | Volume 9 Issue 6 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I6-1712476

From Laboratory Promise to Real-World Performance: Assessing the Deployability of Nano-Tio$_2$ in Self-Cleaning and Air-Purifying Building Material

OLORUNTIMILEYIN T. AKINTADE[1], JOHN A. ADEYEMI[2], SHADE O. ADEMOKOYA[3], MASEALA C. SEKETE[4], TIMOTHY A. ADEYI[5], OLAKUNLE I. ORESEGUN[6]
[1]Department of Civil Engineering, Ekiti State University, Ado-Ekiti, Nigeria
[2]Department of Mechanical Engineering, Lead City University, Off Oba Otudeko Avenue, Lagos-Ibadan Express Way Toll Gate Area, Oyo, Ibadan, Nigeria
[3]Department of Mechanical Engineering, Babcock University, Ilishan Remo, Ogun State, Nigeria
[4]Department of Industrial Design Engineering, Zhejiang University, Hangzhou, China.
[5]School of Automation, Nanjing University of Information Science and Technology, China. Ningliu Road, Nanjing, Jiangsu Province, Nanjing.
[6]Department of Mechanical Engineering, Zhejiang University, Hangzhou, China

Abstract- Nano-titanium dioxide (TiO_2) is currently being strongly sold as a miracle product in the manufacture of air cleaning, cleaning air in buildings in cities. However, there is a huge disparity between perceived and actual performance of a field-level, critical analysis. Although nano-TiO_2 remains the only unquestioned standard photocatalyst due to its unique alkaline stability and bimodal photocatalytic-superhydrophobic activity, its practical operational performance is grossly impaired by three inherent constraints an ultra-environmental response to UV light and soiling akin to all known photocatalysts, extensive scalability demands during manufacturing and cost, and lifecycle immaturity regarding its overall net environmental benefit. This review shows that nowadays the main challenge is not the issue of materials science; it is the issue of practical deployability. The paradigm is thus encouraged to be redefined to revolve around maximizing optimum lab performance to the continuation of its operation in the complex urban settings. Finally, a proper roadmap should be adopted with proper testing plans and industrial standardization and outcome-based policymaking to realize the persuasive vision of nano-TiO_2 into an operable tool to improve environmental health in cities.

Index Terms - Deployability Assessment, Nano-Titanium Dioxide (TiO_2), Photocatalytic Concrete, Real-World Performance Gap, Sustainable Infrastructure

I. INTRODUCTION

Nitrogen oxides (NO_x), and volatile organic compounds and particulate matter released by industries and traffic are the sources of urban air pollution that is a silent but increasing environmental and health risk to the population [1]. To address this, nano-titanium dioxide (TiO2) has been used as a passive method of infrastructure integration in the construction industry. As a component of concrete or as surface treatment, TiO2 uses sunlight to eliminate contaminants and keep surfaces clean, a two-step process [2] photocatalytic oxidation and photoinduced superhydrophilicity. The technology has left the laboratory: it is over St. Louis highways, it is on the walls of the tunnels in Rome (Figure 1), and on the fronts of the most well-known buildings, which gives the perspective of self-cleaning cities.

Nonetheless, there is still a large performance disparity between controlled experiments and real-life conditions. Although laboratory results regularly claim 50 to 90 percent NO_x degradation under idealized UV exposure, field monitoring is indicating much lower values, typically 12 to 20 percent over one year of service [3]. Why? Due to the accumulation of dust on a real urban surface, intermittent sun rays, ruggedness and chemical degradation, which are not readily measured on standard tests such as ISO 22197 or UNI 11259 [4]. Recent heritage mortar research indicates that although TiO2 treatments have an overall cleaning-enhancing effect on rain, performance is highly substrate chemistry and texture-dependent, and that laboratory measurements of dye-degradation do not provide a realistic picture of the actual soiling behaviour [4,5].

This disconnect comes from three problems that haven't been solved yet that make it hard for nano-TiO2 to move from the lab to long-lasting, low-cost infrastructure:

1. Environmental dependency: Performance is degraded when using low-UV conditions, heavy soiling or shaded microclimates, where non-active photocatalysis-induced superhydrophilicity can be counterproductive to biofouling.
2. Scalability gaps: Inadequate standardized mixing technologies, agglomeration and high material prices of nanoparticles inhibit stability in the field performance and industrial implementation.
3. Lifecycle ambiguity: It remains unclear how net environmental gain because a majority of research studies do not consider the full TiO_2 manufacturing footprint, functional deterioration of a product over time and leakages of by-products.

Instead of continuing to talk about the optimistic lab-scale stories, a critical view of nano-TiO_2-enabled building material has been performed using deployability as a metric. Based on field experiments, real-world aging, and new material development, such as doped composites such as BOCN- TiO_2 [6] to the global market dynamics [7], We put together evidence from construction, environmental engineering, and materials science. We don't want to doubt TiO_2's technical abilities; it's clear that it's the only photocatalyst that works in the field and can do a lot of different things. We want to find ways to use it in the real world without being irresponsible.

II. REVIEW METHODOLOGY

This critical review was conducted to synthesize the existing body of literature concerning the application of nano-TiO_2 in building materials with a specific focus on identifying and analyzing the barriers to its real-world deployability. In contrast to the more conventional reviews that primarily catalogue material properties, this analysis adopts a translational science perspective and evaluates the history of the technology as it goes from laboratory promise to real-world performance.

The literature search and selection were structured in such a way that it reflected an overall and modern comprehension of the field. Primary scientific databases, e.g., Scopus, Web of Science, and Google Scholar, were searched based on specific keyword combinations such as nano-TiO_2 photocatalytic concrete, self-cleaning building materials, real-world performance NO_x degradation, lifecycle assessment TiO_2 and photocatalytic standard testing.

The scope of the review prioritized several key areas: Fundamentals of photocatalysis in construction, comparison of TiO_2 with other materials such as ZnO, WO_3, and g-C_3N_4 [7–11].

Recent and Critical Field Evidence: A particular emphasis was placed on studies reporting quantitative field performance data from real-world applications [3,12] and critical analyses that highlight the performance gap between laboratory and urban environments [4,13,14].

Forward-Looking Innovation: We have specifically searched recent publications (2018-2025) on advanced material composites (e.g., BOCN-TiO_2 [6]) and the current review articles that assess the evolving prospects of the technology [7,13,15].

Scalability and Sustainability Metrics: The literature that deal with manufacturing issues [16,17], cost considerations and lifecycle evaluations [18] were included to evaluate economic and environmental feasibility.

The analysis was structured based on a three-part framework of deployability, critically examining evidence related to (i) Environmental Dependency and Functional Decay, (ii) Scalability and Manufacturing Gaps, and (iii) Lifecycle Ambiguity and Net Environmental Benefit. This framework has enabled a systematic integration of evidence across various domains: materials science, environmental engineering, construction management and public policy to provide a holistic and actionable assessment for advancing the field beyond laboratory optimization.

III. NANO-TiO_2 AS THE IDEAL PHOTOCATALYST: A CRITICAL

COMPARISON OF ALTERNATIVES IN THE USE OF CEMENTITIOUS APPLICATIONS.

Although the list of candidate photocatalysts has continued to grow, titanium dioxide (nano- TiO_2) has been unable to be supplanted in any of the cementitious matrices. Its superiority is not just historical, but it is founded on the unique set of material characteristics that match the challenging conditions of concrete. This discussion compares TiO_2 to its best-known substitutes with the thesis that other materials can deliver benefits in the controlled environment. Still, none of them provide the holistic performance and strength necessary to use in a real-life infrastructure setup.

A. TiO_2's Advantages: The Trifecta for Cement Compatibility

The dominance of TiO_2 is pegged on three pillars according to which, it is uniquely suited in concrete.

1. Alkaline Stability: The pore solutions of concrete are very alkaline (pH > 12.5). Compared to most of the semiconductors, which dissolve or corrode in such conditions, TiO2 is extremely chemically inert. According to the article [7], TiO_2 is the best studied and used photocatalyst of PBM as it has high stability, safety and is cost effective [19]. This is due to the stability that guarantees long-term functional persistence in the cement matrix which is a requirement of infrastructure with service lives lasting decades.

2. Dual Photocatalytic and Superhydrophilic Activity: It is the overall feature of TiO_2. It is extremely hydrophilic and is also reactive oxygen species forming when exposed to UV light to oxidize contaminants. [7] specifically states that the behavior of photocatalysts has two significant effects: photodegradation of organic compounds through redox processes; a photoinduced superhydrophilicity, which allows more of the particulate contamination to be removed by rain washing. This two-fold operation is essential: photocatalysis decomposes contaminants, and superhydrophilicity allows rinsing of the residue with the help of rain which makes a celebrated self-cleaning effect necessary in surfaces of urban areas that require low maintenance.
3. Regulatory Acceptance and Industrial Maturity: TiO_2 (particularly anatase) (especially anatase) as a white pigment has been in use since the early twentieth century and today would be found in commercially available products such as Tex Active cement by Italcementi [20,21]. Its high-volume mass manufacture, safety history and site of use in actual-world projects (e.g. in Rome, Dives in Misericordia church [22], St. Louis highways [3]) offer a regulatory and industrial route that up-and-coming options have not matched.

Figure 1. Real-World Validation: Nano-TiO_2 Coating for Tunnel Air Quality Management (adopted from [3])

A. Comparative Analysis of Alternatives: A Reality Check

Regular comparison allows identifying trade-offs that are at the baseline of deployability of TiO_2 alternatives:

1. ZnO: Although [7] states that ZnO is more active as a photocatalyst in aqueous solutions than TiO_2 but balances it by stating that ZnO is not as stable [8,9]. Steady cement constructions are fatally dangerous: ZnO will be dissolved under the high PH (pH > 12.5) to accelerate the performance degradation and may cause microstructural damage [15]. This makes it inappropriate to long-term infrastructure.

2. WO_3/ Fe_2O_3: These visible-light-active photocatalysts deal with the UV dependency of TiO2 but have poor oxidative strength. It is also noted in [7] that such materials as WO_3 and Fe_2O_3 have shown to work successfully in pollutant removal in visible light but their usefulness is constrained by the fact that they have high rates of electron-hole recombination as well as by incomplete degradation pathways [10]. The lack of mineralization will result in the build up of the harmful intermediates at the expense of the environmental benefit.

3. g-C_3N_4: This is a visible-light active, metal-free polymer that is low-cost, however, its viability in practice remains untested. [7] recognizes the potential of g-C_3N_4 but observes that it is restricted in complicated matrices. Importantly, [6] has shown that, even optimized g-C_3N_4, has much lower exhaust degradation efficiency than BOCN-TiO_2 composites that can remove less than half the NO and HC under the same conditions [23]. Furthermore, g-C_3N_4 does not have the long-term weathering stability in the outdoor environment and dispersion characteristics in cement paste, which are important hindrances to cementitious use [7,11].

4. Doped TiO_2 (N-, C-, S-doping): Doping TiO_2's s typically extended into the visible spectrum, but it is usually at the expense of functionality. It is stated that it has demonstrated potential to increase absorption of visible light during doping. It often does away with quantum efficiency and is thermally unstable [24]. The dopant leaching especially in wet and alkaline conditions is a risk especially in the long-term and therefore performance and ecotoxicity are a concern that is also awaiting to be addressed in the field.

B. Insight: The Non-Negotiable Synergy

This analysis implies that at the moment there cannot be found any alternative other than TiO_2 in a synergistic combination whose chemical stability and super hydrophilicity can be compared. According to [3] the self-cleaning capacity in real-life urban conditions not only depends on photodegradation but also on the elimination of particulate matter through rain that is facilitated by superhydrophilicity [4]. A photocatalyst which is capable of breaking down impurities and not cleaning itself will get clogged, and be inaccessible to surface area, and its efficiency will quickly drop, making it useless as a low-maintenance infrastructure.

The important point of such a comparison is that, as much as numerous new photocatalysts have been developed to address the UV light issue of TiO_2, each one of them has a significant drawback that renders them unsuitable in concrete. ZnO itself is unstable, WO_3 and Fe_2O_3 are not so powerful and g-C_3N_4 cannot be long-term stable. Therefore, it is only nano-titanium dioxide that can be used to incorporate an appropriate amount of industrial maturity, self-cleaning and ruggedness to be implemented on real infrastructure. The discovery however is just the initial step to a bigger problem, which is that being an ideal material in the laboratory does not automatically make it good enough in the real world. Even the high level of performance of TiO_2's as the next section will reveal, breaks down in real cities and low UV light, ubiquitous grime and complex surfaces soon make this material useless. It is no longer the problem of finding a material even better but of conquering the mean reality of the environment.

IV. THE DEPLOYABILITY GAP: CRITICAL BARRIERS TO REAL-WORLD PERFORMANCE

Although it has proved successful in the laboratory, nano-TiO_2 has a hard time fulfilling its promises in our cities. There is a wide discrepancy between its potential and actual outcomes. Three key barriers that lead to this deployability gap and which we will now discuss are: first, its failure to perform in the real world in regard to weather and dirt; second, the manufacturing and cost issues of producing it in bulk, and third, the lack of certainty in determining whether it actually has a net environmental benefit.

A. Environmental Dependency and Functional Decay

The difference between the laboratory efficiency of nano-TiO_2 and actual efficiency is extremely wide[3]. Its performance is extremely efficient in the laboratory, but it degrades significantly in the city with its shifting and inaccurate conditions. It is not a small issue, as this failure should be described as elementary because of three reasons: a lack of UV light, dirty surfaces, and the failure of the self-cleaning mechanism in dark spots [13].

The greatest challenge in which TiO_2 can only be active in the ultraviolet (UV) light. Photocatalysis is a process that consumes UV light as noted in [3], and lack of it is one of the major constraints. Some of the places that limit UV light in the urban setting are narrow streets, underpasses or walls that have no sun exposure. In these dark regions, the amount of UV might be below the set threshold to set off the material [15]. This is a natural weakness of TiO_2 characterized by report precisely as the limitation on its application of visible light by a wide band gap [7]. The TiO_2 merely remains inactive in the absence of an appropriate UV lighting. To this issue is added the fact that there is an accumulated amount of grime, soot and dirt on the exterior surfaces [3]. This is because this layer of grime blocks the TiO2 physically so that it cannot absorb light or come into contact with the air pollutants. This is not just a theory. To give an example, laboratory experiments in Chandigarh took 68 percent of nitrogen dioxide out but a real-life experiment in a street in St. Louis showed that the pollutants were reduced by 15 to 20 percent at most in a year on an actual case [3].

The self-cleaning mechanism is one of the massive fallacies. TiO_2 can fulfill two roles: (1) it can decontaminate the pollutants and (2) it can turn into super water-loving (superhydrophilic) that can allow the rain to wipe down dirt [25]. These two effects are complementary to each other, but not complementary of one another. Soot or carbon stains cannot be removed simply by the super water-loving effect. It simply assists water to remove the dirt that has been disintegrated through the photocatalytic reaction. In the shaded areas where the photocatalysis is not operating then the surface-loving can still be water-loving. The impact may however come back to bite since a wet surface may indeed promote the growth of a mold and algae rather than preventing it. This fact is evident in the performance statistics. The removal rates of pollutants in the laboratory tests are usually between 50 and 90% [15]. Nevertheless, practical measurements in urban areas like Rome and St. Louis would always record significantly lower rates, 12 to 20 per cent [3]. Custom test by [4], which simulated urban dirt and rain, established that TiO_2 surfaces were able to self-clean three times well compared to normal surfaces, however, only on the condition that they were first activated by UV light to disintegrate the dirt. The rain could not have done its job without that activation.

The evidence shows that nano-TiO_2 cannot be described as an install and forget technology. Its efficiency is wholly relative to its environment, so a surface which is good in summer sun may be useless in winter, and a wall which is good in a direct sun may be useless in a shade. This basic environmental dependency is the first big challenge that needs to be crossed over to make photocatalytic concrete a viable reality.

B. Scalability and Manufacturing Gaps

Even if nano-TiO_2's environmental performance were completely resolved, it would still be very hard and expensive to move from the lab to widespread construction. These scalability issues make it hard to use at the level needed for city infrastructure consistently and affordably. Money is the most important thing right now. The cost of nano-TiO_2 is many times higher than that of regular Portland cement [16]. Because of this big difference, even small amounts of TiO_2 (usually 2% to 5% by weight of cement) can make things much more expensive. Because it costs more, people choose to use it for larger projects like highways or pavements.

Nanoparticle aggregation is a basic technical problem that has nothing to do with funds. TiO_2 nanoparticles have a lot of energy on their surfaces, so when you mix them, they tend to stick together in bigger groups[17]. When they do this, their effective surface area goes down. This means they are less effective as photocatalysts and are spread out unevenly in the cement matrix. To make a stable, even dispersion, you usually need to use special technologies, such as ultrasonic treatment or chemical dispersants. These things aren't used or needed very often on most construction sites.

The absence of standard protocols exacerbates these issues. Currently, there are no ASTM or EN standards that address the mixing, quality control, or field validation of TiO_2-functionalized concrete [3]. Tests like UNI 11259 for Rhodamine B degradation were made for surfaces that are smooth and even. They don't work well on cementitious surfaces that are rough and porous [4]. These standard tests might not work well on surfaces that are more complicated, which could lead to wrong evaluations of how well something works [3]. This lack of standardization fuels industry caution. Contractors are understandably reluctant to adopt a high-cost, unproven technology without clear performance guarantees or long-term warranties. Without reliable benchmarks, every field application becomes an uncontrolled experiment.

Using pre-blended TiO_2 cement is a good way to get around these issues. The industry could ensure consistent dispersion and get rid of the uncertainty that comes with mixing on-site by adding nano-TiO_2 during the manufacturing process, just like they do with extra cementitious materials like fly ash. Using this method, quality control would move from the job site to the plant. This would let the company grow without hurting performance. There aren't many of these kinds of products yet, and they don't have industry-wide standards yet.

C. Lifecycle Ambiguity and Net Environmental Benefit

The ultimate justification for nano-TiO_2 in infrastructure is its potential to deliver a net environmental benefit, cleaning more pollution over its lifetime than it generates in production. Yet this claim remains unverified, and in many cases, speculative. The upstream environmental burden of nano-TiO_2 is substantial. Its synthesis involves energy-intensive processes, including high-temperature calcination and chemical treatment, which contribute significantly to its carbon footprint. Life cycle assessments indicate that producing 1 kg of nano-TiO_2 can emit 20 to 80 kg of CO_2-equivalent, up to 50 times more per kilogram than ordinary Portland cement, while real-world monitoring suggests a square meter of photocatalytic pavement removes less than 1 g of NO_X per day under typical urban conditions [18]. When this embedded impact is weighed against the material's functional output, the balance is not automatically positive.

Moreover, the operational benefit is likely overestimated. Laboratory studies routinely report 50% to 90% NO_x degradation under ideal UV exposure, but real-world monitoring shows far more modest results, typically 12% to 20% over one year of service in cities like St. Louis and Rome [3]. A comprehensive review of global field trials concluded that even optimized photocatalytic surfaces achieve only about 2% NO_x removal in the immediate vicinity under real urban conditions, and may in some cases degrade local air quality by releasing hazardous by-products such as NO_2 or incomplete oxidation intermediates [14]. If the actual air-cleaning performance is only a fraction of lab projections, the environmental return on investment diminishes sharply.

Equally concerning are the by-products of photocatalysis. The degradation of nitrogen oxides does not eliminate them; it converts them into nitrates and other secondary compounds that can leach from the surface during rain events. These residues may accumulate in soil or water systems, potentially harming ecosystems. Additionally, the long-term stability of nano-TiO_2 in concrete is uncertain, with ongoing questions about nanoparticle leaching and ecotoxicity.

Added to these anxieties are the direct Environmental Health and Safety (EHS) risks of nano-TiO_2 particles at various stages of its life cycle. Although the nanoparticles incorporated in a cured cement matrix are considered to be rather stable, the potential routes of exposure are still important. These are exposure to nanoparticles through inhalation by workers during manufacturing, batching and construction posing potential respiratory hazard [26]. Besides, the duration of the material is important in the long run; abrasion (e.g., road surface or facade) and wear may result in the release of nanoparticles into the environment. The concrete waste is an overwhelming challenge in the process of demolition, where there are no formal, legal guidelines of dealing with nano-enabled construction wastes and this heightens the chances of large-scale environmental spread [27,28]. These released nanoparticles have an ecotoxicological effect on soil and aquatic life, which is also actively studied, and research shows that they have a potential to induce oxidative stress and long-term ecological damage. A proper lifecycle evaluation should thus combine these possible EHS effects so as to actually ascertertain the overall net environmental impact of nano-TiO_2, balancing the intended air purification function against the unintended risks of introducing a new pollutant.

Critically, there is a near-total absence of robust, real-world life cycle assessments (LCA). Most environmental claims rely on optimistic lab-based degradation rates and ignore the full chain of impacts, from production and installation to end-of-life disposal. As [3] acknowledges, in-service performance studies are limited and no study to date integrates realistic decay kinetics, by-product formation, and material longevity into a comprehensive LCA framework. Thus, the central question remains unanswered:

Does nano-TiO_2 concrete truly provide a net environmental gain? Without field-informed lifecycle data, its sustainability credentials rest on assumption, not evidence. Collectively, the challenges of environmental dependency, scalability gaps and the lifecycle uncertainty detailed here form the three core barriers to nano-TiO_2 deployment, as illustrated in Figure 2. This triad of interlocking problems demonstrates that the primary impediment is no longer a lack of laboratory promise, but a failure of real-world deployment. Until this ambiguity is resolved, large-scale deployment risks substituting one environmental problem for another.

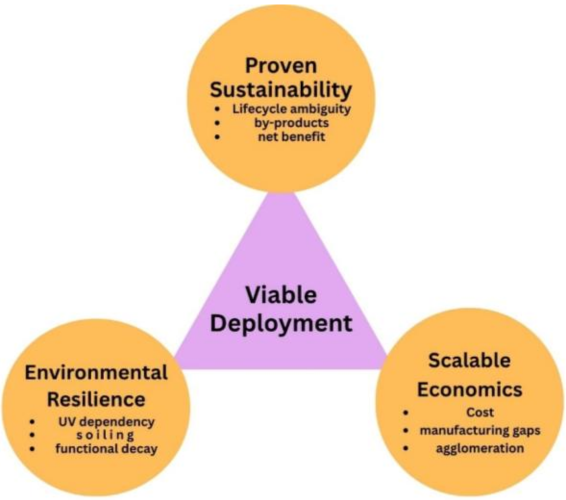

Figure 2. The Three Core Barriers to Nano-TiO_2 Deployment.

V. RECONCILING LABORATORY PROMISE WITH FIELD REALITY: TOWARD A DEPLOYABILITY ASSESSMENT FRAMEWORK

The discrepancy in high performance of nano-TiO_2 in laboratory tests and its low performance in the in real-world urban settings is consistent and well documented. Although standard laboratory procedures such as ISO 22197 or UNI 11259 report 50 to 90 percent NO_x degradation, real field implementation on highways in St. Louis and tunnel linings in Rome report a 12 to 20 percent annual degradation [3,12,14]. This difference stems from a fundamental mismatch: lab tests use idealized conditions such as constant UV light, clean smooth surfaces, and pure pollutant streams, none of which reflect the complexity of real cities. In practice, photocatalytic surfaces face weak or intermittent sunlight, especially in shaded urban canyons, continuous accumulation of dust and soot, biological fouling, and long-term chemical changes at the TiO_2-cement interface. Compounding the problem, current standards often treat photocatalytic oxidation and self-cleaning as interchangeable, when in fact they are distinct processes. Superhydrophilicity helps rain wash away dirt, but only after photocatalysis has broken down hydrophobic pollutants like traffic soot [29,30]. Without sufficient UV activation, as is common in shaded or heavily soiled areas, the surface remains inactive, and its persistent wetness may even encourage microbial growth rather than prevent it [13].

To close this gap, future evaluation of nano-TiO_2 materials must move beyond peak lab performance and focus on functional durability under realistic conditions. A set of minimum criteria for realistic performance assessment is proposed and summarized in TABLE I. This means adopting testing protocols that include cyclic soiling and natural rinsing, using real sunlight or spectrally accurate solar simulators instead of monochromatic UV, monitoring performance over at least six months to capture seasonal and aging effects, and quantifying secondary pollutants such as nitrates that may leach into the environment. Without this shift toward realism, performance claims risk being scientifically sound but practically meaningless for urban infrastructure.

TABLE I
Proposed Minimum Criteria for Realistic Assessment of Photocatalytic Building Materials

Current Standard (e.g., ISO 22197)	Proposed Real-World Criterion	Rationale
Smooth, clean substrate	Rough, porous cementitious surface with controlled soiling (e.g., carbon black + urban dust)	Real facades are textured and accumulate complex grime
Constant UV-A irradiance (1 mW/cm²)	Natural or simulated solar spectrum with diurnal/seasonal variation	Urban UV is intermittent and often < 0.3 mW/cm²
Pure NO gas in dry air	Real urban air or synthetic mix (NO_x + VOCs + PM) at ambient humidity	Pollutants interact; humidity affects reaction pathways
Short-term test (≤ 24 h)	Multi-month exposure with periodic performance checks	Functional decay occurs over time due to fouling/leaching

No by-product analysis	Quantify nitrate, nitrite, and organic intermediates in runoff	Incomplete mineralization may create new hazards

VI. TOWARD DEPLOYABILITY: A FORWARD-LOOKING ROADMAP

Environmental dependency, scalability and lifecycle uncertainty are significant challenges but they are not insurmountable. Overcoming them requires a concerted effort from researchers, industry and policymakers. This roadmap presents concrete, actionable steps toward bringing nano-TiO_2 from lab to firm, real-world infrastructure.

A. For Researchers

Idealized performance must yield to real-world functionality. Instead of observing NO_x destruction under continuous UV irradiation, researchers need to adopt accelerated aging tests that simulate urban environments including cyclical soiling, variable sunlight exposure and natural washing due to rain, as demonstrated in recent studies on heritage mortars. Material innovation should prioritize practical synergies, such as low-dose TiO_2 combined with charge-separation enhancers like graphene oxide, to maintain photocatalytic activity under low-light conditions without significantly increasing cost or complexity.

B. For Industry

Scalability begins with standardization. Pre-blended TiO_2-cement, analogous to how supplementary cementitious materials like fly ash or slag are now routinely supplied, can eliminate on-site mixing uncertainties and ensure consistent nanoparticle dispersion. Industry should also partner with municipalities to launch monitored demonstration projects across diverse climatic and urban contexts, building on precedents such as the two-lift photocatalytic paving in St. Louis. These real-world case studies generate the performance data needed to build contractor confidence, refine design guidelines, and support warranty frameworks.

C. For Policymakers

Incentives need to reward proven environmental impact, not just material content. Tax credits, green public procurement rules or building certification schemes should be tied to measured pollutant removal for example, kilograms of NO_x degraded per square meter per year rather than TiO_2 content alone. Public investment in long-term field monitoring networks would help close the lifecycle assessment gap and provide the empirical foundation needed to develop ASTM or EN standards for real-world photocatalytic performance. These recommendations for key stakeholders are summarized in TABLE II, which provides a concise deployability roadmap to bridge the lab-to-field gap.

TABLE II
Stakeholder Action Plan to Bridge Lab-to-Field Gap

Stakeholder	Key Challenge to Address	Proposed Action Items
Researchers	Environmental Dependency & Functional Decay	• Develop accelerated aging protocols (soiling, rain, low-UV cycles). • Prioritize research on TiO_2-composites for low-light activity. • Quantify and report reaction by-products in runoff.
Industry	Scalability & Manufacturing Gaps	• Invest in and scale up pre-blended TiO_2-cement products. • Partner with cities on diverse, instrumented pilot projects. • Develop industry-wide warranties and performance guarantees
Policymakers	Lifecycle Ambiguity & Adoption Barriers	• Tie green building incentives to *verified* pollutant removal (kg NO_x/m^2/year). • Fund long-term, independent field monitoring networks. • Commission the development of ASTM/EN

	standards for real-world validation.

A Note on Digital Tools

AI-driven "digital twins" could one day simulate how TiO_2 surfaces perform under local UV intensity, pollution levels, and weather patterns. However, as current field studies show, we lack the long-term, high-quality performance data required to train such models reliably. Artificial intelligence cannot compensate for missing real-world validation; it can only organize and extrapolate from data that already exists. Until robust field datasets are established, digital tools will remain speculative rather than predictive.

VII. CONCLUSION

Nano-titanium dioxide stands alone as the only photocatalyst with the alkaline stability, dual photocatalytic–superhydrophilic functionality, and industrial maturity required for infrastructure-scale deployment. Its presence on highways in St. Louis, tunnels in Rome, and landmark facades confirms its technical feasibility. Yet as this review demonstrates, feasibility does not guarantee effectiveness. The persistent gap between laboratory promise, 50–90% NO_x removal, and real-world performance, 12–20% annual reduction, reveals that the primary barrier to impact is no longer materials science, but deployability. Environmental dependency, scalability gaps, and lifecycle ambiguity collectively undermine the assumption that embedding nano-TiO_2 in buildings automatically delivers cleaner air or more sustainable cities.

Moving forward, responsible adoption demands a paradigm shift: from optimizing peak activity under idealized conditions to ensuring durable function under urban reality. This requires researchers to adopt realistic aging protocols, industry to standardize manufacturing and validation, and policymakers to tie incentives to verified outcomes, not material content. The vision of self-cleaning cities remains compelling, but it must be grounded in evidence, not optimism. Only by confronting the messy complexities of real-world performance can nano-TiO_2 fulfill its promise not as a laboratory marvel, but as a genuine tool for urban environmental health.

ACKNOWLEDGMENT

The authors gratefully acknowledge the institutional and technical support received from collaborating universities in Nigeria and China. Their provision of resources and facilities was essential to the successful completion of this research.

REFERENCES

[1] Opeoluwa Oluwanifemi Akomolafe, Tolulope Olorunsogo, Evangel Chinyere Anyanwu, Femi Osasona, Jane Osareme Ogugua, Onyeka Henry Daraojimba. AIR QUALITY AND PUBLIC HEALTH: A REVIEW OF URBAN POLLUTION SOURCES AND MITIGATION MEASURES. Engineering Science & Technology Journal 2024;5:259–71. https://doi.org/10.51594/estj.v5i2.751.

[2] Mandi UA, Meda US, Vora K, Athreya YN. Pollution Control Applications of Nano Titanium Dioxide in the Construction Industry. ECS Trans 2022;107:3281–93. https://doi.org/10.1149/10701.3281ecst.

[3] Bandi G. Photocatalytic Component Used In Concrete For Environmental Friendly Approach. Journal of Scientific Research and Technology 2025;VOLUME:52–9.

[4] Artale A, Fregni A, Franzoni E. About the self-cleaning potential of TiO2-TEOS treatments for heritage cementitious materials. Constr Build Mater 2025;496:143735. https://doi.org/10.1016/j.conbuildmat.2025.143735.

[5] Fregni A, Venturi L, Franzoni E. Evaluation of the Performance and Durability of Self-Cleaning Treatments Based on TiO2 Nanoparticles Applied to Cement-Based Renders and Boards. Coatings 2023;13:990. https://doi.org/10.3390/coatings13060990.

[6] Xu P, Yan X, Ge J, Cai J, Qian G, Yu H, et al. Research on the preparation of composite BOCN-TiO2 photocatalytic materials and their exhaust gas degradation in road domains. Constr Build Mater 2025;494:143584. https://doi.org/10.1016/j.conbuildmat.2025.143584.

[7] Arif M, Hannan Zahid A, Saghir S, Mahsud A. From sunlight to sustainability: The properties, evolution, and prospects of photocatalytic building materials. Catalysis Reviews 2025:1–72.

https://doi.org/10.1080/01614940.2024.2445044.

[8] Messaoud M, Trabelsi F, Kumari P, Merenda A, Dumée LF. Recrystallization and coalescence kinetics of TiO2 and ZnO nano-catalysts towards enhanced photocatalytic activity and colloidal stability within slurry reactors. Mater Chem Phys 2020;252:123235. https://doi.org/10.1016/j.matchemphys.2020.123235.

[9] Li Y, Zhou X, Hu X, Zhao X, Fang P. Formation of Surface Complex Leading to Efficient Visible Photocatalytic Activity and Improvement of Photostabilty of ZnO. The Journal of Physical Chemistry C 2009;113:16188–92. https://doi.org/10.1021/jp9056863.

[10] Mohagheghian A, Ayagh K, Godini K, Shirzad-Siboni M. Enhanced photocatalytic activity of Fe 3 O 4 -WO 3 -APTES for azo dye removal from aqueous solutions in the presence of visible irradiation. Particulate Science and Technology 2019;37:358–70. https://doi.org/10.1080/02726351.2017.1376363.

[11] Majdoub M, Anfar Z, Amedlous A. Emerging Chemical Functionalization of g-C 3 N 4 : Covalent/Noncovalent Modifications and Applications. ACS Nano 2020;14:12390–469. https://doi.org/10.1021/acsnano.0c06116.

[12] Guerrini GL. Photocatalytic performances in a city tunnel in Rome: NOx monitoring results. Constr Build Mater 2012;27:165–75. https://doi.org/10.1016/j.conbuildmat.2011.07.065.

[13] Wei Y, Meng H, Wu Q, Bai X, Zhang Y. TiO2-Based Photocatalytic Building Material for Air Purification in Sustainable and Low-Carbon Cities: A Review. Catalysts 2023;13:1466. https://doi.org/10.3390/catal13121466.

[14] Russell HS, Frederickson LB, Hertel O, Ellermann T, Jensen SS. A Review of Photocatalytic Materials for Urban NOx Remediation. Catalysts 2021;11:675. https://doi.org/10.3390/catal11060675.

[15] Jenima J, Priya Dharshini M, Ajin ML, Jebeen Moses J, Retnam KP, Arunachalam KP, et al. A comprehensive review of titanium dioxide nanoparticles in cementitious composites. Heliyon 2024;10:e39238. https://doi.org/10.1016/j.heliyon.2024.e39238.

[16] Bautista-Gutierrez KP, Herrera-May AL, Santamaría-López JM, Honorato-Moreno A, Zamora-Castro SA. Recent Progress in Nanomaterials for Modern Concrete Infrastructure: Advantages and Challenges. Materials 2019;12:3548. https://doi.org/10.3390/ma12213548.

[17] Sameut Bouhaik I, Leroy P, Ollivier P, Azaroual M, Mercury L. Influence of surface conductivity on the apparent zeta potential of TiO2 nanoparticles: Application to the modeling of their aggregation kinetics. J Colloid Interface Sci 2013;406:75–85. https://doi.org/10.1016/j.jcis.2013.05.034.

[18] Hischier R. Life cycle assessment of engineered nanomaterials. Health and Environmental Safety of Nanomaterials, Elsevier; 2021, p. 443–58. https://doi.org/10.1016/B978-0-12-820505-1.00001-8.

[19] Chen J, Poon C. Photocatalytic construction and building materials: From fundamentals to applications. Build Environ 2009;44:1899–906. https://doi.org/10.1016/j.buildenv.2009.01.002.

[20] Wu XP. A Review - The Properties and Applications of Nano-Structured Titanium Oxide Materials. Key Eng Mater 2017;727:314–21. https://doi.org/10.4028/www.scientific.net/KEM.727.314.

[21] Wu X. Applications of Titanium Dioxide Materials. Titanium Dioxide - Advances and Applications, IntechOpen; 2022. https://doi.org/10.5772/intechopen.99255.

[22] Cardellicchio L. On conservation issues of contemporary architecture: The technical design development and the ageing process of the Jubilee Church in Rome by Richard Meier. Frontiers of Architectural Research 2018;7:107–21. https://doi.org/10.1016/j.foar.2018.03.005.

[23] Li Y, Xing X, Pei J, Li R, Wen Y, Cui S, et al. Automobile exhaust gas purification material based on physical adsorption of tourmaline powder and visible light catalytic decomposition of g-C3N4/BiVO4. Ceram Int 2020;46:12637–47. https://doi.org/10.1016/j.ceramint.2020.02.029.

[24] Mathis JE, Bi Z, Bridges CA, Kidder MK, Paranthaman MP. Enhanced visible-light absorption of mesoporous TiO 2 by co-doping with transition-metal/nitrogen ions. MRS

Proceedings 2013;1547:115–9. https://doi.org/10.1557/opl.2013.666.

[25] Li F, Kong W, Zhao X, Pan Y. Multifunctional TiO 2 -Based Superoleophobic/Superhydrophilic Coating for Oil–Water Separation and Oil Purification. ACS Appl Mater Interfaces 2020;12:18074–83. https://doi.org/10.1021/acsami.9b22625.

[26] Papadaki D, Kiriakidis G, Tsoutsos T. Applications of nanotechnology in construction industry. Fundamentals of Nanoparticles, Elsevier; 2018, p. 343–70. https://doi.org/10.1016/B978-0-323-51255-8.00011-2.

[27] Palaniappan K. Sources Release of Nanoparticles During Construction Activities that could Potentially Pollute the Surrounding Air, 2020. https://doi.org/10.11159/icesa20.03.

[28] Saleem H, Zaidi SJ, Alnuaimi NA. Recent Advancements in the Nanomaterial Application in Concrete and Its Ecological Impact. Materials 2021;14:6387. https://doi.org/10.3390/ma14216387.

[29] Zhang C, Zhang X, Shen H, Shuai D, Xiong X, Wang Y, et al. Superior self-cleaning surfaces via the synergy of superhydrophobicity and photocatalytic activity: Principles, synthesis, properties, and applications. J Clean Prod 2023;428:139430. https://doi.org/10.1016/j.jclepro.2023.139430.

[30] Naef NU, Seeger S. Superhydrophobic Self-Cleaning Membranes Made by Electrospinning. Macromol Mater Eng 2023;308. https://doi.org/10.1002/mame.202200613.