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# A Comprehensive Review of Green Hybrid Polymer–Inorganic Composite Systems Incorporating Palm Tree Ash and Titanium Dioxide

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***Abstract***

*The increasing requests on sustainable and high performance systems have motivated extensive investigations on polymer-based hybrid systems with bio-derived and/or functional inorganic fillers. In this review, the importance of palm tree ash (PTA) and titanium dioxide ($TiO_2$) as synergistic fillers for polymer–inorganic hybrid composites, particularly about structure–property relations, interfacial adhesion and durability performance, is discussed. Agricultural waste-derived palm tree ash (PTA) plays as a silica-rich filler which not only aids matrix densification, filler–matrix adhesion and long-term mechanical stability in polymer composites, but also serves to mitigate an environmental hazard. Conversely, $TiO_2$ is mainly considered as a functional micro- and nanoscale filler, offering an improvement of particle packing, interfacial transition zone behaviour, and stiffness at early ages by means of physical reinforcement and nucleation-like effect in polymer matrices. Current findings from literature reveal that the dual inclusion of PTA and $TiO_2$ results in an enhancement of mechanical strength through synergetic strengthening mechanisms such as higher stress transfer, crack-deflection toughness and microstructural homogeneity than the individual fillers. While related densification processes are frequently cited in the context of inorganic binder systems, this review also discusses how related performance improvement trends can be translated into polymer composite design, particularly for thermoset and polymer-binder based systems. Overall, the investigated PTA–TiO2 based hybrid polymer composite offers an attractive route to the production of green multifunctional composite materials following the principles of circular economy and sustainable polymer engineering, thus paving the way for further technological advancements.*

**Keywords:** Polymer composites; Polymer–inorganic hybrid composites; Functional fillers; Palm tree ash; Titanium dioxide; Structure–property relationships; Sustainable polymer materials

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## INTRODUCTION

Polymer composites are becoming important advanced materials with a wide range of applications in aerospace, automotive, bio-medical, energy, and infrastructure fields owing to their high strength-to-weight ratio, design flexibility, corrosion resistance, and tailorable functional properties. The progressive developments of thermoset polymers, thermoplastic matrices and polymer-based binders have motivated intense research toward composite systems containing functional fillers and hybrid reinforcements for desired mechanical performance, longevity, and sustainability. In the past decades, the focus on advancing green polymer composites systems with bio-based or waste-derived fillers with reduced environmental impact and at the same time agreeing the structural performance was gaining more and more attention. High silica content oil palm tree ash (PTA) is a new potential candidate as agro waste filler in polymer composites among which oil palm-derived PTA has the potential to improve filler–matrix interaction and thus useful for sustainable material design. On the other hand, titanium dioxide ($TiO_2$) has been widely studied as functional micro- and nano-scale additives in polymer composites, as it can improve the stiffness, interfacial adhesion and superficial properties. Together with bio-based fillers like PTA, $TiO_2$ allows for hybrid polymer–inorganic composite systems that result in synergistic reinforcing mechanisms which are not attainable employing single-filler strategies [1].

Although PTA and $TiO_2$ have been the subject of intense research in inorganic binder and cementitious systems, their possible functions as functional fillers in polymer-based composite matrices are still relatively underexplored and scattered across the literature. Adapting concepts from such as particle packing, microstructural densification and crack resistance in inorganic systems to the engineering of polymer composites provides new avenues for the development of multifunctional, green polymer composites [2]. For this reason, the present review is aimed at discussing critically the use of PTA and $TiO_2$ in polymer and polymer-binder composite systems, with special attention given to the structure–properties, filler–matrix interaction, processing issues and durability of the resultant systems [3]. A comparative representation of palm tree ash (PTA), titanium dioxide ($TiO_2$), and ordinary Portland cement (OPC), highlighting their material characteristics and roles in composite binder systems, is shown in Figure 1.

## Literature Review

### *Polymer Composite Systems and Filler Reinforcement Mechanisms*

Polymer composites have been widely advanced in response to increasing need of light weight and high performance materials with customized mechanical and functional properties. In the case of polymer matrix composites, the efficiency of reinforcement is mainly related to filler dispersion, interfacial adhesion, particle morphology and polymer matrix compatibility [4]. These factors have a direct influence on stress transfer, crack generation and aging, and this has been the motivation for research on hybrid systems in which two or more fillers are combined in the hope of obtaining synergistic improvements in the structure–property relationship [5].


**Figure 1.** Comparison of palm tree ash (PTA) and titanium dioxide ($TiO_2$) with ordinary Portland cement (OPC) used in composite binder systems.

 

***Bio-Derived Fillers in Polymer Composites***

The utilization of bio-based and waste-based fillers has been established as a promising approach to the production of sustainable polymer composites with less environmental burden. Agricultural residues converted into silica-based fillers have been found to foster stiffness, decrease voids, and improve dimensional stability of polymer matrices. Palm tree ash (PTA) has gained interest owing to its good particle size and together with polymer binder, the filler–matrix interlocking and mechanical stabilisation in the composite is enhanced when the filler is added at an optimum loading level.

***Titanium Dioxide as a Functional Filler in Polymer Matrices***

$TiO_2$ has been extensively studied as an active micro/nanoparticle filler in polymer composites, mainly because of its capability to improve stiffness, wear resistance and surface durability. It has been reported that $TiO_2$ enhances the composite performance mainly through the physical strengthening mechanisms, such as better particles packing, limitation of polymer chain motion and modification of interfacial transition regions. Moreover, $TiO_2$ also provides multi-functional advantages, such as UV protection and surface stability, which could make it an interesting enhancer for high-performance polymer composite applications. [6]

***Hybrid Polymer–Inorganic Composite Systems***

The recent trends in the research on the polymer–inorganic composites are focused on the introduction of hybrid systems using bio based fillers and functional inorganic additives to exploit synergistic effects. The two-stage effect exerted by combination PTA/TiO2 allows complementary reinforcing mechanisms: PTA provides better stability/sustainability of the bulk matrix, TiO2 leads to better interfacial adhesion as well as early-stage stiffness. 3–10 Indeed, while significant enhancements in crack resistance and durability have been documented,10 the literature is still scattered, and systematic assessment of the structure−property relationships and the long-term behavior of PTA−$TiO_2$-based polymer composite systems is required [7].

**Some Observations from the Table**

- The studies tabulated suggest that palm tree ash (PTA) is a sustainable bio-filler for the polymer composites, which plays a vital role in enhancing the matrix densification and mechanical stability at the suitable filler content.
- Titanium dioxide ($TiO_2$) also imparts pronounced enhancements of the early-stage stiffness and interfacial properties for polymer systems due to the micro- and nanoscale filling effects and the more efficient particle packing.
- The hybrid polymer composite made of PTA and $TiO_2$ demonstrates better stress distribution and crack resistance than single-filler system, illustrating the synergy of different reinforcements.
- Particulate size, dispersion quality, and the compatibility between filler and matrix hugely affect the performance of PTA−$TiO_2$ hybrid composites, suggesting the necessity of a regulated processing.
- There are reports showing that overloading of fillers influence could potentially cause agglomeration and the deterioration of mechanical performance, suggesting the importance of tailoring the composite formulation.
- Thanks to the enhanced microstructural uniformity, other durability-related features such as water-resistance and dimensional stability are also significantly improved in the hybrid polymer composites [8].

**Research Gaps**

The growing demand for sustainable fillers for polymer composites has led to the focus of research on palm tree ash (PTA) and titanium dioxide ($TiO_2$) as single-filler system, their synergism effect as hybrid system in polymer composite system has not been given much consideration. There is little investigation on the dispersion, interfacial adhesion with, and reinforcing efficiency of the PTA–$TiO_2$ fillers as a function of the polymer matrix type (e.g., thermoset, thermoplastic and polymer modified binder). Stress transfer, crack deflection and microstructural uniformity of hybrid polymer composite are not well stablished yet. Moreover, influence of processing conditions such as mixing procedure, filler functionalization and curing route on the structure–property correlations of PTA–$TiO_2$ polymer composites has not been sufficiently elucidated. Durability performance over extended period of time including exposure of environmental aging, moisture and thermal cycling have been reported with high variations. Besides, very few comprehensive life-cycle and sustainability evaluations targeting polymer-based hybrid composites with bio-derived fillers exist, which hinders the possibility to fully exploit the potential environmental and functional benefits compared to traditional polymer composite systems [9].

## Critical Analysis of Existing Studies

Previous studies on palm tree ash (PTA) and titanium dioxide ($TiO_2$) based composites materials reveal that the strength and stability are considerably enhanced, yet most of the research are still on a small scale and without any uniform experimental protocol. Polymer composite studies Direct comparisons of results in polymer composite studies are complicated by differences in the type of polymer matrix, levels of filler loading, particle size distribution, and dispersion technique. Of studies reporting enhancements in performance, a significant pool do so with insufficient characterization of filler–matrix interfacial interactions, which underpin mechanisms of reinforcement such as stress transfer, crack deflection and matrix confinement effects. Nevertheless, most of the documented works focus on short-term mechanical properties and the long-term stability and durability of PTA–$TiO_2$ polymer composites remain rarely evaluated. Processing challenges such as filler agglomeration, poor interfacial compatibility, scalability of fabrication methodologies are recognized but not quantitatively described. Also, sustainability arguments typically refer to filler source rather than on full life-cycle analysis. Such limitations serve to motivate systematic polymer-centric investigations of processing–structure–property with long-term performance based on reliable methodologies for design of hybrid polymer composite systems [10].

## Mechanical Interactions Between Palm Tree Ash (PTA) and Titanium Dioxide ($TiO_2$)

In the polymer based composites, the mechanical interaction of palm tree ash (PTA) and titanium dioxide (TiO2) is due to the synergistic effect of the bio-based filler and the functional inorganic filler. PTA enhances the stability of the bulk matrix by promoting filler–matrix interlocking and impeding polymer chain movement, which translates into an effective load transfer and long-term mechanical stability. $TiO_2$ at both micro- and nano-scales facilitates the interfacial reinforcement, via better packing of particles, and the re-distribution of localized stresses, resulting in improved stiffness and resistance to the initiation of microcracks. PTA and $TiO_2$ exhibit a complementary influence since both possess different reinforcement mechanisms that enhance stress transfer efficiency, crack deflection, and microstructure homogeneity within the polymer matrix compared to single-filler polymer systems. A comparative summary of the mechanical behavior and functional roles of PTA and $TiO_2$ in composite binder systems is provided in Table 1.

**Table 1.** Mechanical Behavior Influence: PTA vs $TiO_2$

| **Behavior Aspect** | **PTA** | **$TiO_2$** |
|---|---|---|
| Early-age strength | Moderate or delayed | Strong acceleration |
| 28–90 day strength | Significant increase via secondary C–S–H | Mild increase; effect saturates |
| Workability | Slight improvement at micro; reduction at nano | Reduction due to high surface area |
| Microcracking | Reduced (gel densification) | Reduced (pore refinement) |
| Cement matrix | Long-term stability | Early nucleation stabilization |

 

**Figure 2.** Stages of recycling: (a) typical date palm tree, (b) raw waste, (c) grinding and molding machine

**Methodology of the Review Process**

This review was carried out via a systematic review of the peer-reviewed literature concerning polymer composite systems with the inclusion of bio-based and/or inorganic fillers, focusing on palm tree ash (PTA) and titanium dioxide (TiO). To ensure alignment with polymer science and composite engineering, the following keywords were employed polymer composites, functional fillers, hybrid composites, $TiO_2$ nanoparticles, biomass-derived fillers [5]. The general processing and recycling stages of palm tree waste, from raw biomass to processed ash suitable for composite binder applications, are illustrated in Figure 2.

The included studies were assessed for the type of polymer matrix, the characteristics of the filler, processing methods, and the described structure–property relationships. Specific focus was on the behavior of the dispersion of the filler, the mechanism of the interfacial bonding, the shape and the size of the filler, the mechanical performance and the durability trends when in the polymer matrix. The comparative examination was carried out to evaluate the dominant reinforcing mechanisms, the hybrid fillers synergistic effect and the existing research limitations. This strategy facilitated the determination of critical gaps and future directions important for the development of sustainable polymer composites [6] A schematic overview of PTA- and $TiO_2$-modified cementitious composite systems and their interaction within the binder matrix is presented in Figure 3.

**Trends and Developments in the Field**

In polymer composite research, a new trend is the raising interest toward hybrid filler systems to obtain a balanced mechanical performance with a lower environmental impact. The use of bio-based fillers in polymer matrices has become increasingly attractive as a means to reduce material cost and improve sustainability without sacrificing structural performance. Novel polymer processing methods, such as advanced mixing, surface chemistry modification of fillers, and dispersion management, have allowed the incorporation of non-traditional fillers into thermoset and polymer-binder systems with greater effectiveness. Also of interest is the emerging use of functional micro-scale and nano-scale fillers to improve interfacial and multi-functionality for polymer composites. Titanium dioxide ($TiO_2$) has been extensively investigated for enhancing the stiffness, surface stability and interfacial strength. The combination of bio-based fillers such as PTA with functional additives like TiO2 sugars the path towards advanced hybrid polymer composites, in which different (competing) reinforcement mechanisms are purposefully combined to tailor structure–property relations. [11].

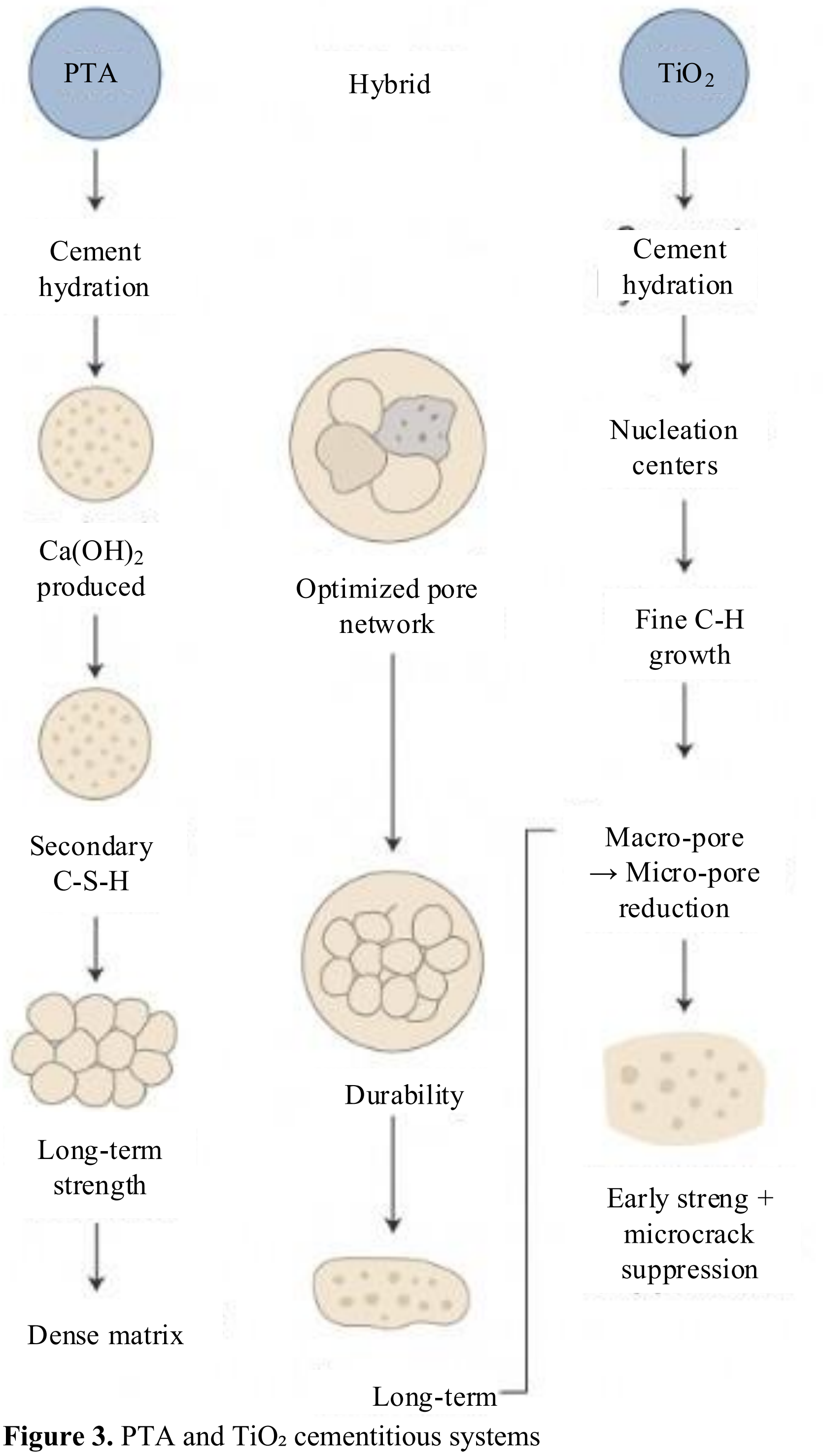


**Figure 3.** PTA and $TiO_2$ cementitious systems

**Comparative Evaluation of Palm Tree Ash (PTA) and Titanium Dioxide ($TiO_2$)**

Palm tree ash (PTA) and titania ($TiO_2$) have different reinforcing mechanism in the polymer composite matrix. PTA acts mainly as a bio-derived particulate filler that leads to densification of the matrix, improved filler–matrix interlocking and long-term mechanical performance. Its silica-rich nature and irregular particle shape enable mechanical interlocking and stress transfer in polymer matrices, especially at optimum filler loading. The key material characteristics, functional roles, and performance implications of palm tree ash and titanium dioxide in cementitious composite systems are compared in Table 2. [12].

 

**Table 2.** Aspects of PTA and $TiO_2$

| Aspect | Palm Tree Ash (PTA) | Titanium Dioxide ($TiO_2$ / Nano-$TiO_2$) |
|---|---|---|
| **Material Type** | Supplementary cementitious material (SCM), pozzolanic | Nanomaterial additive, non-pozzolanic |
| **Primary Function** | Cement replacement; reacts with $Ca(OH)_2$ to form additional C–S–H | Hydration accelerator; nucleation sites for C–S–H growth |
| **Typical Usage Level** | 1–5% cement replacement (mass basis) | 0.5–2% of cement (by weight of binder) |
| **Chemical Activity** | Consumes portlandite → increases secondary C–S–H → enhances long-term properties | Physical effect (nano-scale) → no $Ca(OH)_2$ consumption → modifies early microstructure |
| **Effect on Strength** | Moderate early gain; strong improvement at 28–90 days | Strong early gain (1–7 days); modest long-term influence |
| **Workability** | May slightly improve or reduce depending on fineness; larger particles increase flow | Generally reduces workability due to high surface area; requires dispersants |
| **Durability** | Improves permeability, chloride resistance, sulphate resistance via matrix densification | Refines nano-pore structure; enhances UV resistance; reduces surface degradation |
| **Environmental Impact** | Waste valorization; reduces clinker demand; lower embodied $CO_2$ | High energy synthesis; used in small amounts; indirect sustainability via performance |
| **Functional Features** | No photocatalytic properties | Photocatalytic, self-cleaning, pollutant degradation ($NO_x$ / organics) |
| **Microstructural Role** | Generates secondary C–S–H; fills microvoids; reduces $Ca(OH)_2$ | Creates nucleation centers; stabilizes gel growth; reduces microcrack initiation |
| **Limitations** | Excessive replacement → binder dilution; variability due to ash source | Agglomeration at high dosage; cost; property plateau beyond optimal content |
| **Best Used For** | Sustainable concrete, durability enhancement, cement reduction | Performance boost, surface functionality, high-performance/rapid-strength mixes |

On the other hand, $TiO_2$ serves as a functional micro- or nano-sized filler that improves interfacial interactions due to better particle packing and induced local stress field rearrangement. $TiO_2$ particles hinder the motion of polymer chains in the vicinity of the filler surface, which results in hardening and better resistance to initiation of microcracks. Although PTA mainly plays a role in stabilizing and sustaining the bulk composite, $TiO_2$ provides interfacial reinforcement and early mechanical response. Their tandem introduction allows for hybrid polymer composites that combine the long-term stability with increased stiffness and toughness [13].

### Parameters Influencing Strengthening Efficiency

The reinforcing effectiveness of PTA and $TiO_2$ in polymer composites is influenced by a number of interdependent factors such as filler particle size, dispersion quality, filler load, polymer matrix, and processing conditions. Homogeneous distribution and good filler–matrix adhesion are critical for stress transfer and crack resistance, whereas too high filler content might cause agglomeration and consequent mechanical degradation. Interfacial bonding and microstructural uniformity are further affected by surface chemistry, mixing techniques and curing processes, highlighting the need to the best composite formulation for attaining synergistic reinforcement [14]. The influence of PTA and $TiO_2$ on durability-related properties and microstructural refinement in composite binders is summarized in Table 3.

### Durability and Long-Term Performance of Palm Tree Ash (PTA) and Titanium Dioxide ($TiO_2$)

The stability of the microstructure and the interfacial integrity are very important for the long-term performance of PTA–$TiO_2$ polymer composites. Dimensional stability and microstructural defects are improved by PTA and resistance to microcrack propagation is increased by $TiO_2$ through interfacial reinforcement and stress redistribution [15]. The two fillers together resulted in even finer microstructures with superior resistance to environmental aging, moisture exposure, and mechanical fatigue, leading to the development of potentially long-lived/sustainable polymer composite systems. The physical and chemical characteristics of PTA and $TiO_2$ relevant to their performance in cementitious composite systems are presented in Table 4.

 

**Table 3. Effects on Durability and Microstructure**

| **Durability Aspect** | **PTA Contribution** | **$TiO_2$ Contribution** |
|---|---|---|
| Permeability | ↓ via pore refinement | ↓ via nano-filling |
| Chloride ingress | ↓ by densified C–S–H | ↓ surface penetration |
| Sulphate resistance | ↑ because lower $Ca(OH)_2$ | Neutral → slight ↑ |
| Carbonation | ↓ due to fewer pores | Not directly affected |
| Freeze–thaw | ↑ gel stability | ↑ reduced microcracks |
| Surface pollution | No effect | Self-cleaning photocatalysis |

**Table 4.** Physical and Chemical Characteristics of PTA and $TiO_2$ in Cementitious Systems

| **Parameter** | **Palm Tree Ash (PTA)** | **Titanium Dioxide ($TiO_2$ / Nano-$TiO_2$)** |
|---|---|---|
| Material origin | Agricultural residue (biomass ash) | Industrial by-product or engineered nanomaterial |
| Particle size | 1–75 µm (micro) / <100 nm (nano) | 20–200 nm |
| Major composition | $SiO_2$, $Al_2O_3$, CaO, $K_2O$ | $TiO_2$ (anatase/rutile) |
| Reactivity | Pozzolanic – consumes $Ca(OH)_2$ | Non-pozzolanic – nucleation sites |
| Replacement/addition | 5–15% cement replacement | 0.5–2% cement addition |
| Environmental impact | Reduces clinker → lower $CO_2$ | No clinker reduction → functional benefits |

## SUMMARY

This review focused on palm tree ash (PTA) and titanium dioxide ($TiO_2$) as an interesting functional filler material for polymer composites and polymer–inorganic hybrids systems, and discussed the reinforcement mechanism, processing behaviour, and the property results. The literature investigated reveals that the bio-derived filler, palm tree ash (PTA) promotes composite sustainability by enhancing matrix densification, filler–matrix interlocking, and mechanical stability over time. $TiO_2$ as a micro or nano-size scale inorganic filler significantly contributes to interfacial reinforcement, stiffness and stress redistribution within polymer matrices by physical interaction mechanisms. Combined incorporation of the PTA and $TiO_2$ as a hybrid system is a promising approach for designing polymer composites with superior enhancement of structure–property. Due to synergy between fillers, combined microstructures were more refined, crack resistant and transferred stress more uniformly than the single fillers system. However, the review also reveals that there is a considerable heterogeneity in terms of the type of polymer matrix, filler loading, dispersion methods, and testing procedures, which hampers a direct comparison of the results among the studies. These findings carve out new, polymer-centric experimental paradigms that ought to be fulfilled in order to successfully realize the sustainable and high-performance hybrid polymer composites. The fundamental mechanisms and performance benefits associated with the incorporation of PTA and $TiO_2$ in hybrid composite binder systems are summarized in Figure 4.

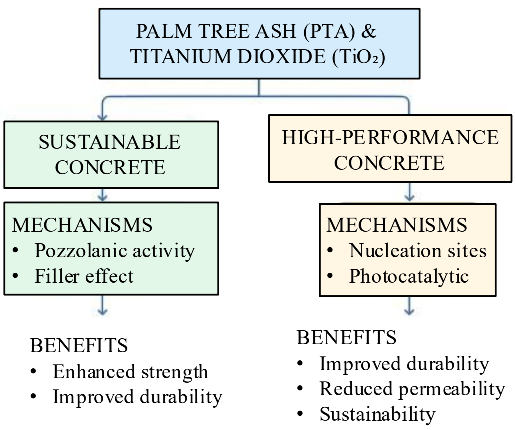


**Figure 4.** Mechanisms and Benefits of PTA and $TiO_2$

## CONCLUSION

The reinforcing effects of palm tree ash (PTA) and titanium dioxide ($TiO_2$) are complementary in nature and provide a great potential for the development of high performance and greener polymer composite materials. PTA contributes to bulk composite stability enhancement via mechanical interlocking and matrix confinement mechanisms, and at the same time, to environmental friendliness through the recovery of biomass derived waste. In contrast, $TiO_2$ enhances interfacial properties by improving filler dispersion, confining polymer chain diffusion, and retarding microcrack formation and cleavage. The synergy between the two phases, PTA and TiO2, thus pursuing hybrid polymer composites that yield a compromise between sustainability, mechanical efficiency and durability.

While promising performance enhancements, present studies are constrained by the limited knowledge of polymer-specific interfacial processes, long-term durability behavior, and processing technique scalability. Further research will be directed toward the systematic characterization of polymer–filler interactions, the fine-tuning of hybrid filler compositions, and the monitoring of microstructural evolution under environmental and mechanical aging. The inclusion of life-cycle assessment and multifunctional performance analysis will also facilitate the bridging of the gap for PTA–$TiO_2$ hybrid polymer composites from laboratory-scale research to practical engineering use.

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