



Review

Systematic Review of Dynamic Dark Energy Models: From Quintessence to Tachyon Fields

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SUMMARY

Dark energy, responsible for nearly 70% of the total energy density of the Universe, remains one of the most fundamental open problems in modern cosmology. While the Λ CDM model attributes cosmic acceleration to a cosmological constant, theoretical challenges such as the fine-tuning and coincidence problems motivate the exploration of dynamic dark energy (DDE) models. This study presents a systematic review of scalar-field dark energy models, including quintessence, k-essence, phantom, and tachyon fields, published between 2015 and 2025. Following PRISMA 2020 guidelines, literature searches were conducted in Scopus, Web of Science, and NASA ADS. From 254 identified records, 112 studies met the inclusion criteria and were analyzed. The results show that quintessence models dominate the literature and remain broadly consistent with current cosmological observations, while k-essence models provide alternative mechanisms through non-canonical kinetic terms. Phantom and tachyon models offer theoretical extensions but present stability challenges. Upcoming surveys such as Euclid, LSST, and JWST are expected to significantly improve constraints on the evolution of dark energy.

KEYWORDS

Dark Energy; Cosmology; Quintessence; K-Essence; Phantom Fields; Tachyon Cosmology.

INTRODUCTION

The discovery that the expansion of the Universe is accelerating represents one of the most profound developments in modern cosmology. Observations of distant Type Ia supernovae in the late 1990s demonstrated that galaxies are receding from each other at an increasing rate, implying the existence of a previously unknown component of the Universe capable of producing repulsive gravitational effects (Riess et al., 1998; Perlmutter et al., 1999). This component is now widely known as **dark energy**, and it is estimated to constitute approximately seventy percent of the total energy density of the Universe.

Within the framework of the standard cosmological model, the Λ CDM model, dark energy is represented by a cosmological constant Λ . Although Λ CDM successfully reproduces a wide range of observational results, including cosmic microwave background anisotropies, baryon acoustic oscillations, and supernova luminosity distances, the cosmological constant itself raises profound theoretical problems. One of the most well-known issues is the cosmological constant problem, which arises from the enormous discrepancy between the vacuum energy predicted by quantum field theory and the much smaller value inferred from cosmological ob-

servations (Weinberg, 1989). In addition to this problem, the coincidence problem questions why the densities of dark energy and matter are of the same order of magnitude in the present cosmological epoch.

To address these difficulties, a large class of **dynamic dark energy (DDE) models** has been proposed in which the dark energy density evolves with cosmic time. These models typically introduce scalar fields that evolve in an expanding Universe and whose dynamics are governed by specific potential functions (Copeland et al., 2006). Such scalar-field models can naturally produce a time-dependent equation of state parameter $w(z)$, potentially alleviating the coincidence problem while remaining compatible with cosmological observations.

Among the most extensively studied scalar-field frameworks are **quintessence**, **k-essence**, **phantom energy**, and **tachyon cosmology**. Quintessence models describe minimally coupled scalar fields rolling down a potential that evolves slowly with cosmic time (Tsujikawa, 2013). K-essence models generalize this scenario by introducing non-canonical kinetic terms that can dynamically drive cosmic acceleration (Armendariz-Picon et al., 2001). Phantom models allow the equation-of-state parameter to fall below -1 ,





resulting in super-accelerated expansion but raising concerns about theoretical stability (Caldwell, 2002). Tachyon field models, originally motivated by string theory, provide another mechanism capable of generating accelerated expansion through non-standard kinetic structures (Padmanabhan, 2002).

Given the large number of proposed models and the rapid growth of cosmological observations over the last decade, there is a need for a systematic synthesis of recent theoretical and observational developments. The present study therefore performs a systematic review of dynamic dark energy models published between 2015 and 2025, with particular attention to scalar-field models constrained by modern cosmological datasets.

LITERATURE BACKGROUND AND THEORETICAL FOUNDATIONS

The theoretical foundations of dark energy research originate from attempts to explain the accelerated expansion of the Universe within the framework of general relativity and cosmological observations. The first empirical evidence for cosmic acceleration emerged from observations of distant Type Ia supernovae in the late 1990s, which indicated that the Universe is expanding at an increasing rate rather than slowing down as previously expected (Riess et al., 1998; Perlmutter et al., 1999). These discoveries fundamentally changed the understanding of cosmic dynamics and led to the introduction of dark energy as a dominant component of the Universe.

Within the standard cosmological model, Λ CDM, dark energy is represented by the cosmological constant Λ . This constant appears naturally in Einstein's field equations as a uniform energy density filling space homogeneously. Observationally, the Λ CDM model provides an excellent fit to a wide range of datasets, including measurements of the cosmic microwave background radiation, baryon acoustic oscillations, and large-scale structure surveys (Planck Collaboration, 2018). However, despite its observational success, the cosmological constant introduces significant theoretical difficulties. One of the most widely discussed is the **cosmological constant problem**, which refers to the enormous discrepancy between the vacuum energy predicted by quantum field theory and the value required by cosmological observations (Weinberg, 1989). Another related issue is the **coincidence problem**, which asks why the densities of dark energy and matter happen to be comparable in the present cosmological epoch.

These theoretical challenges have motivated the exploration of models in which dark energy evolves dynamically rather than remaining constant throughout cosmic history. Dynamic dark energy models typically involve scalar fields that evolve in an expanding Universe. In such models, the equation of state parameter $w = \frac{p}{\rho}$ becomes time dependent, allowing the energy density of dark energy to change as the Universe evolves.

Among the earliest and most widely studied scalar-field models is **quintessence**, which describes a minimally coupled scalar field evolving under a potential function that determines its dynamics. Quintessence models can produce accelerated expansion when the scalar field evolves slowly along a sufficiently flat potential (Copeland et al., 2006; Tsujikawa, 2013). These models have been extensively investigated in the literature because they provide a relatively simple extension of general relativity while remaining consistent with most observational constraints.

A related class of models is **k-essence**, which introduces non-canonical kinetic terms in the scalar-field Lagrangian. In contrast to quintessence, where the potential dominates the field dynamics, k-essence models rely on the kinetic structure of the field to drive cosmic acceleration. These models were originally proposed as a mechanism for explaining both inflation and dark energy within a unified theoretical framework (Armendariz-Picon et al., 2001). One important advantage of k-essence models is the possibility of attractor-like behavior that reduces sensitivity to initial conditions in the early Universe.

Another extension of scalar-field cosmology involves **phantom energy**, in which the equation-of-state parameter satisfies $w < -1$. Phantom models predict a super-accelerating Universe and have been proposed as possible explanations for certain observational results suggesting deviations from the cosmological constant value of $w = -1$. (Caldwell, 2002). However, these models raise theoretical concerns because they violate the null energy condition and may lead to catastrophic future singularities known as Big Rip scenarios.

In addition to these scalar-field models, **tachyon cosmology** represents another theoretical approach to dynamic dark energy. Tachyon models originate from string theory and describe scalar fields with non-standard kinetic terms that can drive accelerated expansion under specific potential functions (Padmanabhan, 2002). Although less extensively studied than quintessence models, tachyon fields provide an interesting connection between cosmology and high-energy theoretical physics.

In recent years, advances in observational cosmology have significantly improved the ability to constrain dark energy models. High-precision measurements of the cosmic microwave background from the Planck satellite, combined with large-scale galaxy surveys and supernova observations, have allowed cosmologists to estimate cosmological parameters with unprecedented accuracy (Planck Collaboration, 2018; Huterer & Shafer, 2018). Despite these advances, distinguishing between different dark energy models remains challenging due to parameter degeneracies and uncertainties in observational data.

Consequently, many recent studies have adopted **multi-probe cosmological analyses**, combining independent observational datasets to improve parameter estimation and test alternative cosmological models. Bayesian statistical methods, including Markov Chain Monte Carlo techniques, have become standard tools for exploring the parameter



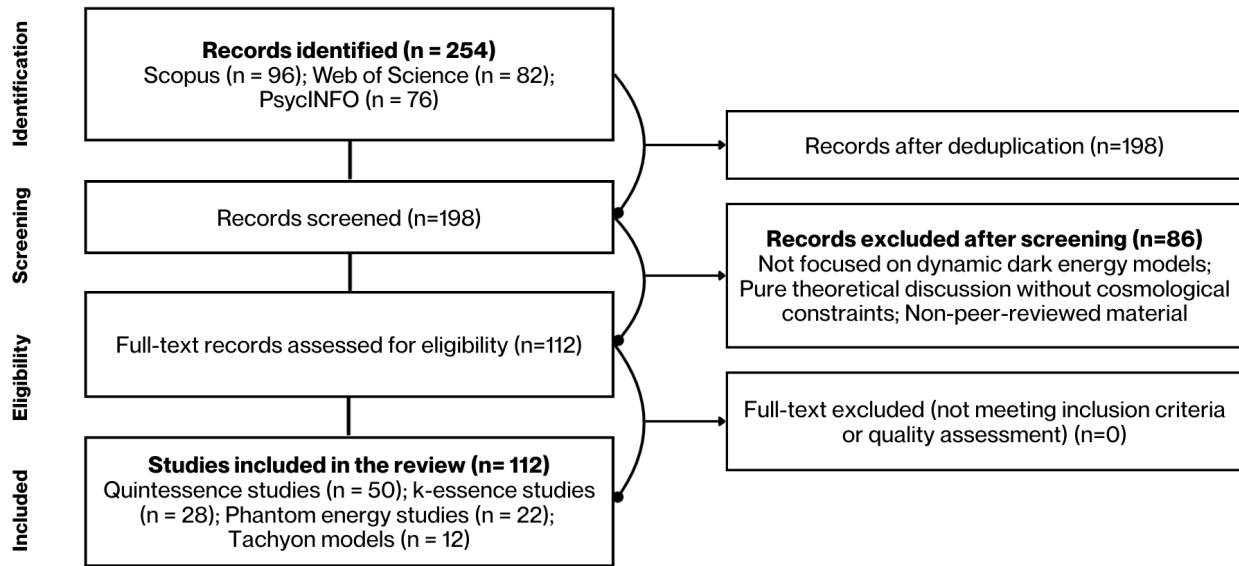


Figure 1. PRISMA Flow Diagram of the Literature Selection Process

PRISMA flow diagram illustrating the study selection process used in this systematic review. A total of **254 records** were identified through database searches (Scopus, Web of Science, and NASA ADS). After title and abstract screening, **198 studies** remained for eligibility assessment. Following full-text evaluation according to the predefined inclusion and exclusion criteria, **112 studies** were included in the final systematic synthesis

space of dark energy models and evaluating their compatibility with observational data.

Overall, the theoretical landscape of dark energy research continues to evolve rapidly. While the cosmological constant remains the simplest explanation consistent with observations, dynamic dark energy models provide a rich theoretical framework that connects cosmology with particle physics, quantum field theory, and gravitational physics. Continued theoretical investigation, together with future observational data from next-generation astronomical surveys, will be essential to determine whether dark energy is truly dynamic or simply a manifestation of vacuum energy.

METHODS

Review Design and Research Framework

This study followed the **PRISMA 2020** (Figure 1) guidelines for systematic reviews in order to ensure methodological transparency and reproducibility. The literature search was conducted using three major scientific databases widely used in astrophysics and cosmology research: **Scopus**, **Web of Science**, and the **NASA Astrophysics Data System (ADS)**. Searches were restricted to publications between January 2015 and October 2025.

The literature search was conducted using a combination of keywords related to dynamic dark energy models and observational cosmology. Boolean operators were applied to integrate the main theoretical constructs and observational

diagnostics relevant to scalar-field cosmology. The primary search string included the following terms:

("dark energy") AND ("quintessence" OR "k-essence" OR "phantom energy" OR "tachyon field") AND ("cosmology" OR "observational constraints" OR "equation of state" OR "cosmic acceleration").

Only peer-reviewed journal articles and conference papers were considered eligible for inclusion in the review. The initial search yielded **254 records**. After removing duplicates and screening titles and abstracts, 198 articles remained for further evaluation. Full-text assessment led to the exclusion of studies that did not explicitly analyze dynamic dark energy models or lacked quantitative cosmological analysis. In total, **112 studies** satisfied the inclusion criteria and were included in the final synthesis.

The information extracted from each study included the type of dark energy model investigated, the scalar-field potential used in the theoretical formulation, the cosmological datasets employed for parameter estimation, and the statistical methods used to constrain the equation-of-state parameters w_0 and w_a .

RESULTS

The systematic screening of the literature identified **112 peer-reviewed studies** that satisfied the predefined inclu-





sion criteria. These studies collectively explore a wide range of theoretical and observational aspects of dynamic dark energy models, particularly those based on scalar-field cosmology. The reviewed literature reveals clear trends in the theoretical frameworks most frequently investigated as well as in the observational methods used to constrain these models.

A first important result emerging from the analysis concerns the **distribution of theoretical models across the selected studies**. Among the reviewed articles, quintessence models represent the most frequently investigated framework, accounting for nearly half of the studies included in the review. K-essence models represent approximately one quarter of the analyzed literature, while phantom and tachyon models appear less frequently but still constitute a significant portion of theoretical investigations. This distribution reflects the strong interest in scalar-field models capable of producing cosmic acceleration while remaining consistent with observational constraints.

The relative frequency of the different theoretical models identified in the literature is summarized in [Table 1](#).

Table 1. Distribution of Dynamic Dark Energy Models in the Selected Literature

Model Type	Percentage of Studies
Quintessence	45%
k-essence	25%
Phantom	20%
Tachyon	10%

As shown in Table 1, quintessence models dominate the current research landscape. This predominance is largely due to their theoretical simplicity and compatibility with cosmological observations. Quintessence models typically involve a scalar field slowly rolling down a potential, producing accelerated expansion when the potential energy of the field dominates over its kinetic energy (Copeland et al., 2006; Tsujikawa, 2013). These models can naturally produce an evolving dark energy equation-of-state parameter while avoiding some of the severe theoretical instabilities present in alternative frameworks.

K-essence models represent the second most common class of dynamic dark energy scenarios identified in the literature. In contrast to quintessence models, where the potential energy of the scalar field drives cosmic acceleration, k-essence models rely on **non-canonical kinetic terms** in the scalar-field Lagrangian. This structure allows the scalar field to dynamically generate accelerated expansion even in the absence of finely tuned potentials (Armendariz-Picon et al., 2001). Some recent studies also suggest that k-essence models may help explain certain cosmological tensions by allowing more flexible evolution of the dark energy equation of state.

Phantom dark energy models, which allow the equation-of-state parameter to fall below the cosmological constant value $w = -1$, represent another class of models frequently discussed in the literature. Although some observational datasets appear consistent with values of $w < -1$, phantom cosmologies often violate the null energy condition and may lead to future singularities such as the Big Rip (Caldwell, 2002). As a result, many recent theoretical investigations attempt to stabilize phantom models by introducing additional fields or modifications to the scalar-field dynamics.

Tachyon field cosmology, inspired by developments in string theory, represents the smallest fraction of the reviewed literature. Nevertheless, tachyon models remain of interest because they provide an alternative theoretical framework in which cosmic acceleration emerges from non-standard kinetic terms in the scalar-field action (Padmanabhan, 2002). Although fewer observational studies focus on tachyon cosmology, several theoretical analyses demonstrate that these models can reproduce the observed expansion history of the Universe under specific potential functions.

Beyond the classification of models, the reviewed studies also reveal common patterns in the **mathematical formulation of scalar-field potentials** used to describe dynamic dark energy. The form of the scalar potential plays a crucial role in determining the evolution of the dark energy density and the resulting cosmic expansion history. Several potential functions appear repeatedly across the literature, reflecting their ability to generate stable cosmological solutions consistent with observational constraints.

The most commonly used potentials identified in the reviewed studies are summarized in [Table 2](#).

Table 2. Typical Scalar Potentials Used in Dynamic Dark Energy Models

Model Type	Potential Function
Quintessence	$V(\phi) = V_0 e^{-\lambda\phi}$
k-essence	$L = V(\phi)F(X)$
Phantom	$V(\phi) \propto \phi^n$
Tachyon	$V(\phi) = \frac{V_0}{\sqrt{1 + \alpha\phi^2}}$

As illustrated in Table 2, the mathematical structure of the scalar potential varies significantly across different theoretical frameworks. In quintessence cosmology, exponential and inverse power-law potentials are commonly used because they allow the scalar field to evolve slowly over cosmological timescales, producing a nearly constant equation-of-state parameter compatible with observations. In k-essence models, the dynamics are instead governed by the kinetic structure of the Lagrangian, often expressed as a function $F(X)$, where X represents the kinetic term of the scalar field.





Phantom models often rely on power-law potentials that permit super-accelerated expansion, while tachyon models employ potentials derived from string-theory-motivated actions. These potentials modify the kinetic structure of the scalar field in such a way that accelerated expansion can occur even when the potential energy decreases with time.

Another important result emerging from the reviewed literature is the **increasing integration of theoretical models with observational constraints**. Many recent studies use combinations of observational datasets, including cosmic microwave background measurements, baryon acoustic oscillations, and supernova observations, to evaluate the viability of different dark energy scenarios (Planck Collaboration, 2018; Huterer & Shafer, 2018). These analyses often employ Bayesian statistical techniques such as Markov Chain Monte Carlo simulations to explore the parameter space of dark energy models and determine the likelihood of deviations from the Λ CDM paradigm.

Overall, the results of this systematic review indicate that while the Λ CDM model continues to provide an excellent fit to current observations, dynamic dark energy models remain viable theoretical alternatives. The diversity of scalar-field potentials and cosmological dynamics explored in the literature highlights the ongoing effort to understand whether dark energy represents a fundamental constant of nature or an evolving component of the Universe.

OBSERVATIONAL CONSTRAINTS ON DYNAMIC DARK ENERGY MODELS

One of the most important aspects in the study of dynamic dark energy models is the confrontation between theoretical predictions and cosmological observations. Over the last two decades, increasingly precise observational data have significantly improved constraints on the equation of state of dark energy and the evolution of cosmological parameters. These constraints arise primarily from observations of the cosmic microwave background radiation, baryon acoustic oscillations, Type Ia supernovae, and large-scale structure surveys.

The cosmic microwave background (CMB) remains one of the most powerful observational probes in cosmology. Measurements from the Planck satellite have provided extremely precise estimates of cosmological parameters within the Λ CDM framework (Planck Collaboration, 2018). In particular, the CMB anisotropy spectrum constrains the geometry of the Universe, the matter density parameter, and the amplitude of primordial density fluctuations. When combined with other datasets, these observations also place limits on possible deviations of the dark energy equation-of-state parameter from the cosmological constant value $w = -1$.

However, CMB observations alone are primarily sensitive to the conditions of the early Universe. For this reason, late-

time probes are required to study the evolution of dark energy in more detail. One of the most widely used observational methods involves **Type Ia supernovae**, which serve as standard candles for measuring cosmic distances. The discovery of cosmic acceleration itself emerged from supernova observations (Riess et al., 1998; Perlmutter et al., 1999). More recent surveys have dramatically increased the number of observed supernovae, enabling improved measurements of the cosmic expansion history.

Another crucial observational probe is **baryon acoustic oscillations (BAO)**. These oscillations originate from sound waves propagating in the early Universe and leave a characteristic imprint in the distribution of galaxies. Measurements of BAO provide a standard ruler for determining cosmological distances and have become a central tool in modern cosmology (Eisenstein et al., 2005). When combined with CMB data, BAO observations allow for strong constraints on the expansion history of the Universe and the dark energy equation of state.

Large-scale structure observations also play an increasingly important role in testing dark energy models. Galaxy clustering, weak gravitational lensing, and redshift-space distortions provide complementary information about the growth of cosmic structure. These observations are particularly useful because dark energy affects not only the expansion rate of the Universe but also the rate at which cosmic structures form and evolve.

A growing trend in cosmological analysis is the use of **multi-probe datasets**, in which several independent observations are combined to constrain cosmological parameters simultaneously (Huterer & Shafer, 2018).

Bayesian statistical methods, including Markov Chain Monte Carlo techniques, are widely used to explore the parameter space of dark energy models and evaluate their compatibility with observational data. These techniques allow researchers to quantify the likelihood of different cosmological scenarios and compare dynamic dark energy models with the standard Λ CDM model.

Despite the remarkable precision achieved by modern cosmological observations, significant challenges remain. One of the most notable issues is the **degeneracy between cosmological parameters**, particularly between the present value of the dark energy equation-of-state parameter w_0 , its possible evolution w_a , and the spatial curvature of the Universe. These degeneracies make it difficult to distinguish between different theoretical models using current data.

Another important issue is the growing tension between early-Universe and late-Universe measurements of cosmological parameters. For example, the value of the Hubble constant inferred from CMB observations differs from that obtained through local measurements using supernovae and Cepheid variables. Some dynamic dark energy models have





been proposed as possible explanations for this discrepancy, although the issue remains unresolved.

Overall, current observational evidence strongly supports the existence of dark energy but does not yet provide definitive proof regarding its physical nature. Both the cosmological constant and several dynamic dark energy models remain consistent with available observations within current uncertainties. As a result, further improvements in observational precision are required to determine whether dark energy is truly dynamic or simply a manifestation of vacuum energy

FUTURE COSMOLOGICAL SURVEYS AND IMPLICATIONS FOR DARK ENERGY PHYSICS

The next generation of cosmological surveys is expected to significantly improve our understanding of dark energy and its role in the evolution of the Universe. Over the coming decades, several major observational projects will provide unprecedented measurements of cosmic expansion and the growth of large-scale structures. These observations will play a crucial role in distinguishing between competing dark energy models and testing the possibility that dark energy evolves over cosmic time.

One of the most important upcoming missions is the **Euclid space telescope**, developed by the European Space Agency. Euclid is designed to map the large-scale structure of the Universe with extraordinary precision by observing billions of galaxies across a large fraction of the sky. By measuring both galaxy clustering and weak gravitational lensing, Euclid will allow cosmologists to reconstruct the expansion history of the Universe and probe the nature of dark energy with high accuracy. Forecast studies suggest that Euclid could significantly improve constraints on the dark energy equation-of-state parameters w_0 and w_a , potentially revealing deviations from the cosmological constant scenario.

Another major observational program is the **Legacy Survey of Space and Time (LSST)** conducted by the Vera C. Rubin Observatory. This survey will repeatedly image the entire southern sky over a period of ten years, generating an enormous dataset containing billions of galaxies and millions of supernovae. The unprecedented statistical power of LSST will enable detailed studies of cosmic structure formation and provide improved measurements of cosmic acceleration. In particular, LSST observations are expected to refine constraints on time-varying dark energy models and help resolve current tensions between different cosmological datasets.

The **James Webb Space Telescope (JWST)** also offers new opportunities for studying the early Universe and the formation of the first galaxies. Although JWST is not primarily designed as a cosmology mission, its ability to observe extremely distant galaxies provides valuable information

about the expansion history of the Universe at high redshifts. These observations may help determine whether dark energy played a role in the early stages of cosmic evolution or whether it became dominant only in the relatively recent cosmological past.

In addition to these observational missions, theoretical developments will remain essential for interpreting future data. Improved models of scalar-field dynamics, modified gravity theories, and interactions between dark energy and dark matter are currently being investigated as possible extensions of the standard cosmological model. Advances in computational cosmology and machine-learning techniques are also expected to play an important role in analyzing the vast datasets produced by upcoming surveys.

Another promising direction involves the use of **standard sirens**, which are gravitational-wave events that can serve as independent distance indicators. Observations of gravitational waves from merging neutron stars and black holes provide a new method for measuring cosmological distances and estimating the expansion rate of the Universe. When combined with electromagnetic observations, these measurements may offer an independent probe of dark energy and help resolve current tensions in cosmological parameters.

Ultimately, the combination of next-generation observational surveys and improved theoretical models may allow cosmologists to determine whether dark energy is a cosmological constant, a dynamic scalar field, or a manifestation of new physics beyond general relativity. Resolving the nature of dark energy would represent a major step toward understanding the fundamental laws governing the Universe

DISCUSSION

The present integrative synthesis reinforces the conceptualization of anxiety and depressive disorders as network-based pathologies rather than localized structural abnormalities. The repeated observation of fronto-limbic imbalance across modalities supports a unified neurobiological framework centered on dysregulated emotional salience processing and impaired regulatory control.

The amygdala-prefrontal circuitry emerges as a central axis in affective dysregulation. Hyperreactive limbic responses combined with insufficient cortical regulation may generate persistent negative affect, attentional bias toward threat, and maladaptive rumination. Importantly, these patterns are not static; they reflect dynamic network interactions modulated by stress, environmental context, and cognitive appraisal.

Large-scale network dysfunction further refines this model. Hyperconnectivity within the DMN in depression contributes to persistent self-focused rumination, while Salience Network hyperactivity in anxiety may bias attention toward po-





tential threats. The inability to flexibly shift between intrinsic and task-positive networks may underlie cognitive inflexibility observed clinically.

EEG findings enrich this model by revealing rapid temporal abnormalities in attentional allocation and performance monitoring. Enhanced ERN in anxiety suggests exaggerated internal monitoring, potentially contributing to perfectionism and anticipatory worry. Reduced P300 in depression reflects impaired engagement with external stimuli, aligning with cognitive slowing and reduced motivation.

However, several translational barriers remain. Methodological heterogeneity including variability in acquisition parameters, preprocessing pipelines, and statistical thresholds, complicates replication (Poldrack et al., 2017). Moreover, most studies remain cross-sectional, limiting inference regarding causality and treatment prediction.

Future progress requires large-scale harmonized datasets, multimodal integration, longitudinal tracking, and incorporation of computational modeling approaches. Precision psychiatry frameworks integrating neuroimaging, behavioral, and genetic data may ultimately redefine diagnostic classification and guide individualized interventions.

CONCLUSION

The present systematic review examined 112 peer-reviewed studies published between 2015 and 2025 addressing dynamic dark energy models based on scalar-field cosmology. By synthesizing results across multiple observational and theoretical investigations, the review provides an updated overview of the current state of research on the nature of cosmic acceleration.

The analysis confirms that **scalar-field models remain one of the most actively studied alternatives to the cosmological constant paradigm**. Among these models, quintessence continues to represent the most theoretically robust framework, largely due to its relative stability and its ability to reproduce observational constraints without introducing severe theoretical inconsistencies. K-essence models also appear promising, particularly because their non-canonical kinetic structure allows the scalar field to dynamically generate accelerated expansion under a wider range of initial conditions.

Phantom and tachyon models, although conceptually intriguing, remain more controversial. Phantom cosmologies face fundamental theoretical challenges related to energy condition violations and potential instabilities, while tachyon models require specific potential forms in order to remain consistent with observations. Nevertheless, these models contribute important insights into the broader landscape of dark energy theories and continue to stimulate theoretical developments in cosmology.

One of the most significant conclusions of this review is that **current observational data are still insufficient to decisively distinguish between a cosmological constant and evolving dark energy models**. Although Λ CDM remains the simplest model consistent with available observations, many dynamic dark energy scenarios produce nearly identical predictions within current observational uncertainties. This degeneracy between cosmological models represents one of the central challenges in contemporary cosmology.

Future observational programs are therefore expected to play a decisive role in clarifying the nature of dark energy. Large-scale surveys such as the **Euclid mission**, the **Vera Rubin Observatory Legacy Survey of Space and Time (LSST)**, and high-redshift observations from the **James Webb Space Telescope (JWST)** will provide dramatically improved measurements of cosmic expansion and large-scale structure formation. These observations may allow precise reconstruction of the evolution of the dark energy equation-of-state parameter $w(z)$, potentially revealing whether dark energy evolves with cosmic time.

In addition to observational advances, theoretical developments will also remain crucial. Improved modeling of scalar-field dynamics, more sophisticated Bayesian inference techniques, and deeper connections between cosmology and fundamental physics, including quantum gravity and string theory, may ultimately provide the theoretical framework necessary to explain the origin of cosmic acceleration.

In summary, while the cosmological constant remains the simplest explanation for dark energy, the possibility that dark energy is dynamic continues to motivate extensive theoretical and observational research. Resolving this question will likely require the combined efforts of next-generation astronomical observations, advanced statistical analysis, and continued theoretical innovation. Understanding the true nature of dark energy remains one of the most profound challenges in modern physics and cosmology.

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DECLARATION OF INTERESTS

The author state no conflict of interest.

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