

Original article

Rényi Holographic Dark Energy in Higher-Dimensional Self-Creation Cosmology: The General Relativity Limit

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Abstract

In this study, a higher-dimensional flat Friedmann–Robertson–Walker (FRW) universe model filled with pressureless matter and Rényi holographic dark energy is investigated within the framework of self-creation cosmology. By adopting a specific parametrization of the Hubble parameter, exact analytical solutions of the field equations are obtained, and the cosmological dynamics of the model are analyzed. The results show that the model consistently describes an expanding universe with a dynamically evolving dark energy component. The equation of state parameter ω evolves toward negative values at late cosmic times and remains within the quintessence region, providing a consistent description of late-time accelerated expansion without entering the phantom domain. Furthermore, the self-creation scalar field Φ is found to be constant, implying that the field equations effectively reduce to a form equivalent to General Relativity with a modified coupling term. Thus, the model does not yield an independent dynamical self-creation solution but instead corresponds to the General Relativity limit of the theory. Despite this reduction, the inclusion of Rényi holographic dark energy leads to a physically viable cosmological scenario.

Keywords: Self Creation Cosmology, FRW Universe, Higher Dimensional Cosmology, Rényi Holographic Dark Energy, Hubble Parameter Parametrization

Received: 21 August 2026 * **Accepted:** 12 October 2026 * **Published:** 24 October 2026

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INTRODUCTION

The discovery of the late-time accelerated expansion of the universe, supported by various observational data sets such as type Ia supernovae (SN Ia), cosmic microwave background (CMB), and baryon acoustic oscillations (BAO), has led to the development of numerous cosmological models aiming to explain this phenomenon (Riess et al., 1998; Perlmutter et al., 1999; Spergel et al., 2003; Eisenstein et al., 2005). Within the standard cosmological framework, this acceleration is commonly attributed to dark energy, a hypothetical component characterized by negative pressure. Despite its success, the nature and origin of dark energy remain among the most fundamental open problems in modern cosmology (Copeland et al., 2006). Alternative gravitational theories have been proposed as possible extensions or modifications of General Relativity (GR) to account for the observed cosmic acceleration. One such approach is self-creation cosmology, which introduces a scalar field coupled to the gravitational sector, allowing for matter creation within the cosmic evolution (Barber, 1982, 1983). This framework modifies the standard Einstein field equations and provides a different perspective on the interplay between geometry and matter fields. However, an important question in such theories is whether they yield genuinely new cosmological dynamics or effectively reduce to GR under certain conditions. Bhabor et al. (2016) have obtained exact solutions in Barber's second self-creation theory within the framework of a Bianchi type-I universe filled with a perfect fluid. Prasanthi et al. (2025) have investigated a dark energy cosmological model in Bianchi type-V space-time within self-creation gravity. Daimary and Baro (2025) have studied self-creation cosmology in a five-dimensional Bianchi type-I universe filled with a Reddy string. Tade and Nimkar (2026) have investigated a spatially homogeneous and anisotropic Bianchi type-V cosmological model in Barber's second self-creation theory of gravitation with a thick domain wall and bulk viscous fluid and have obtained exact solutions under Berman's law of variation of the Hubble parameter.

On the other hand, holographic dark energy models, inspired by the holographic principle, provide a promising approach to describing the dark energy component (Li, 2004). Generalized entropy formalisms such as Tsallis and Rényi entropy have recently been employed to construct modified holographic dark energy models (Tsallis & Cirto, 2013; Biró & Czinner, 2013; Czinner & Iguchi, 2016; Moradpour et al., 2018; Sheykhi, 2018). The resulting Rényi holographic dark energy models have been shown to exhibit interesting cosmological behavior and have attracted considerable attention in recent studies. Motivated by these developments, it is of particular interest to investigate the cosmological implications of Rényi holographic dark energy within alternative gravitational frameworks such as self-creation cosmology. Moreover, higher-dimensional cosmological models provide additional degrees of freedom and have been widely studied in the literature to better understand the early- and late-time behavior of the universe (Singh & Singh, 1991; Sahoo & Reddy, 2016). Santhi et al. (2024) have studied Rényi holographic dark energy in anisotropic Marder-type space-time within Saez-Ballester scalar-tensor theory by considering the Hubble and Granda-Oliveros cutoffs and have obtained quintom-like

behavior consistent with accelerated cosmic expansion. Prasanthi and Neelima (2025) have developed anisotropic and spatially homogeneous Bianchi type-V Rényi holographic dark energy models in Brans–Dicke theory and have analyzed their cosmological dynamics and stability for the Hubble and Granda–Oliveros cutoffs. Battaloğlu and Aktaş (2025) have analyzed Rényi holographic dark energy in homogeneous anisotropic Bianchi type-I cosmology and have obtained exact solutions whose behavior has been examined using different observational data sets. Abdelrashied et al. (2026) have examined Rényi holographic dark energy in an inhomogeneous isotropic universe with interacting dark sectors and have found good agreement with recent observations through cosmological, stability, and thermodynamic analyses. Malakar et al. (2026) have reconstructed an $f(R)$ gravity model based on Kaniadakis holographic dark energy in FLRW space-time and have demonstrated its theoretical viability in describing the late-time accelerated expansion of the universe. Sireesha et al. (2026) have investigated Barrow holographic dark energy models within the Brans–Dicke framework by considering interacting and non-interacting scenarios and have analyzed their cosmological dynamics, stability, and consistency with observational data. Prasuna et al. (2026) have studied Rényi holographic dark energy within Brans–Dicke scalar-tensor theory for flat and non-flat FLRW universes and have shown its viability in explaining late-time cosmic acceleration through dynamical and observational analyses. Karimi and Malekolkalami (2026) have investigated a generalized holographic dark energy model with a varying parameter ($C=C(z)$) in a flat FRW universe and have shown that the model can describe late-time accelerated expansion with quintessence, phantom, or Big Rip scenarios.

In this work, we consider a higher-dimensional flat Friedmann–Robertson–Walker (FRW) universe model filled with pressureless matter and Rényi holographic dark energy within the framework of self-creation cosmology. By adopting a specific parametrization of the Hubble parameter, we obtain exact analytical solutions of the field equations and analyze the resulting cosmological dynamics. Special attention is given to the behavior of the scalar field and to the extent to which the model deviates from or reduces to General Relativity. Aditya and Reddy (2018) have investigated FRW-type Kaluza–Klein cosmological models with modified holographic Ricci dark energy in Brans–Dicke theory and have obtained models compatible with present-day cosmological observations. Pradhan et al. (2022) have studied Barrow holographic dark energy in Brans–Dicke theory for non-flat FRW universes and have obtained a quintom-like evolution together with observationally consistent results based on 46 Hubble data points. Dasunaidu et al. (2023) have studied Kaluza–Klein FRW Tsallis holographic dark energy models in Saez–Ballester scalar-tensor gravity and have shown that the models exhibit accelerated cosmic expansion consistent with Planck observational data through dynamical and stability analyses. Das et al. (2024) have investigated Tsallis holographic dark energy in a flat FRW universe with cold dark matter, have obtained exact solutions by adopting the hybrid expansion law, and have analyzed the resulting physical and geometrical parameters.

The paper is organized as follows. In Section 2, the basic field equations of self-creation cosmology and the formulation of Rényi holographic dark energy are presented. In Section 3, the analytical solutions of the model are obtained, and the cosmological parameters are analyzed graphically. Section 4 is devoted to a discussion of the results, with particular emphasis on the General Relativity limit and its physical implications. Finally, the main conclusions of the study are summarized in Section 5.

MATERIAL AND METHODS

Self-Creation Cosmological Field Equations

Barber's second theory of self-creation cosmology (SCC) introduces a scalar field represented by the function Φ into the gravitational interaction, and the SCC field equations can be written as follows.

$$R_{ij} - \frac{1}{2}g_{ij}R = -\frac{8\pi}{\Phi}T_{ij} \quad (1)$$

where R_{ij} is the Ricci tensor, R is the Ricci scalar, g_{ij} is the metric tensor, T_{ij} is the energy-momentum tensor, and Φ represents the self-creation scalar field (Barber, 1982). The scalar field satisfies the following wave equation:

$$\square\Phi = \Phi^k_{;k} = \frac{8\pi}{3}\lambda T \quad (2)$$

here λ is the coupling constant and T denotes the trace of the energy-momentum tensor (Barber, 1982, 1983). In this framework, the scalar field Φ plays an important role in determining the effective gravitational interaction.

Higher-Dimensional Flat FRW Space-Time

In this study, the homogeneous and isotropic higher-dimensional flat FRW space-time is considered. The $(n+2)$ -dimensional flat FRW metric is written as:

$$ds^2 = dt^2 - A^2(t)[dr^2 + r^2 d\chi_n^2] \quad (3)$$

where $A(t)$ denotes the scale factor and $d\chi_n^2$ represents the line element of the n -dimensional angular part, which is given by (Singh & Beesham, 2012):

$$d\chi_n^2 = d\theta_1^2 + \sin^2 \theta_1 d\theta_2^2 + \sin^2 \theta_1 \sin^2 \theta_2 d\theta_3^2 + \dots + \sin^2 \theta_1 \sin^2 \theta_2 \dots \sin^2 \theta_{n-1} d\theta_n^2 \quad (4)$$

For the higher-dimensional flat FRW universe, the Hubble parameter is defined as

$$H = \frac{1}{n+1} \frac{\dot{V}}{V} = \frac{\dot{A}}{A} \quad (5)$$

where $V = A^{n+1}$ denotes the spatial volume function of the $(n+2)$ -dimensional FRW universe, and the overdot represents differentiation with respect to cosmic time t , i.e., $\dot{A} = dA/dt$.

Matter Distribution and Rényi Holographic Dark Energy

The universe model is assumed to consist of two components: pressureless matter with energy density ρ_m and Rényi holographic dark energy with energy density ρ_r and pressure p . Therefore, the total energy-momentum tensor of the cosmic fluid is taken as (Battaloğlu & Aktaş, 2025)

$$T_{ij} = (\rho_m + \rho_r + p)u_i u_j - p g_{ij} \quad (6)$$

where u^i is the $(n+2)$ -dimensional velocity vector given by

$$u^i = (1, 0, 0, \dots, 0) \quad (7)$$

The total energy density of the model is therefore expressed as

$$\rho = \rho_m + \rho_r \quad (8)$$

By taking the Hubble horizon as the infrared cutoff, the energy density of Rényi holographic dark energy is expressed as

$$\rho_r = \frac{3s^2 H^2}{1 + \pi \eta H^{-2}} \quad (9)$$

where s is a dimensionless holographic model parameter and η is the non-extensive Rényi parameter (Aktaş & Yılmaz, 2024; Dubey et al., 2020).

Field Equations for the Model

Using the self-creation field equations together with the higher-dimensional flat FRW metric and the energy-momentum tensor defined above, the field equations for the considered universe model are obtained as

$$n\dot{H} + \frac{n(n+1)}{2}H^2 = -\frac{8\pi p}{\Phi} \quad (10)$$

$$\frac{n(n+1)}{2}H^2 = \frac{8\pi(\rho_m + \rho_r)}{\Phi} \quad (11)$$

These equations describe the dynamical evolution of the scale factor, the matter energy density, the Rényi holographic dark energy density, the pressure, and the self-creation scalar field. The conservation equation for the total energy-momentum tensor is given by

$$T^i{}_{j;j} = 0 \quad (12)$$

For the present higher-dimensional flat FRW universe filled with matter and Rényi holographic dark energy, this condition gives

$$\dot{\rho}_m + \dot{\rho}_r + (n+1)H(\rho_m + \rho_r + p) = 0 \quad (13)$$

The system of field equations contains more unknown quantities than independent equations. Therefore, an additional physically motivated assumption is required. The Hubble parameter $(H=\dot{A}/A)$ is a fundamental cosmological quantity that characterizes the relative expansion rate of the Universe and describes the time evolution of cosmic expansion. Parametrizing the Hubble parameter has been widely employed in cosmological studies as a convenient approach for constructing and analyzing different expansion histories. In particular, Pacif et al. (2017) proposed a general time-dependent parametrization of the Hubble parameter encompassing several cosmological models. In the present study, we adopt one of its particular forms (Model VI)

$$H = \frac{\beta}{\sqrt{t+\alpha}} \quad (14)$$

where α and β denote positive constants. This choice provides a simple time-dependent description of the cosmic expansion and enables an analytical treatment of the cosmological field equations. For positive values of α and β , H remains positive and decreases monotonically with cosmic time, describing an expanding Universe with a decreasing Hubble rate.. Substituting this parametrization into the Rényi HDE given by Eq. (9), one obtains

$$\rho_r = \frac{3s^2\beta^4}{[\pi\eta(t+\alpha)+\beta^2](t+\alpha)} \quad (15)$$

RESULTS

In this section, exact solutions of the field equations are obtained for the higher-dimensional flat FRW universe filled with pressureless matter and Rényi holographic dark energy within the framework of self-creation cosmology. Using the Hubble parameter given in Eq. (14), we have

$$\frac{\dot{A}}{A} = \frac{\beta}{\sqrt{t+\alpha}} \quad (16)$$

Integrating Eq. (16), the scale factor is obtained as

$$A = c_1 e^{2\beta\sqrt{t+\alpha}} \quad (17)$$

where c_1 is an integration constant. This result shows that the scale factor is expressed in terms of an exponential function of $\sqrt{t+\alpha}$. Using Eqs. (10), (11), and (13), together with the Rényi HDE density given in Eq. (15), the self-creation scalar field Φ is obtained as

$$\Phi = \frac{16c_1\pi^2}{n(n+1)\beta^2} \quad (18)$$

The matter energy density ρ_m is obtained in the following form

$$\rho_m = \frac{c_1\pi}{t+\alpha} - \frac{3s^2\beta^4}{[\pi\eta(t+\alpha)+\beta^2](t+\alpha)} \quad (19)$$

Using Eqs. (15) and (19), the total energy density can be written in the simple form

$$\rho_m + \rho_r = \frac{c_1 \pi}{t + \alpha} \quad (20)$$

Furthermore, the pressure of the Rényi HDE component is obtained as

$$p = - \frac{[-1 + \beta(n+1)\sqrt{t+\alpha}]\pi c_1}{(t+\alpha)^{3/2}\beta(n+1)} \quad (21)$$

The equation of state (EoS) parameter of the Rényi holographic dark energy is defined by

$$\omega = \frac{p}{\rho_r} \quad (22)$$

Substituting Eqs. (15) and (21) into Eq. (22), the EoS parameter becomes

$$\omega = - \frac{[-1 + \beta(n+1)\sqrt{t+\alpha}]\pi c_1 [\pi \eta(t+\alpha) + \beta^2]}{3s^2 \beta^5(n+1)\sqrt{t+\alpha}} \quad (23)$$

The obtained solution set forms the basis for the physical interpretation of the model and will be discussed in detail in the following section.

DISCUSSION

The exact solutions obtained in the previous section provide important insights into the higher-dimensional flat FRW Rényi holographic dark energy model within self-creation cosmology. First, the solutions satisfy the field equations given by Eqs. (10) and (11), together with the conservation equation given by Eq. (13). Therefore, the obtained solution set is mathematically consistent within the framework of the present model. A remarkable feature of the solution set is associated with the self-creation scalar field given in Eq. (18). This expression shows that the scalar field reduces to a constant determined by the model parameters c_1 , n , and β . Consequently, the dynamical contribution expected from the self-creation scalar field does not appear in the present solution set. In this respect, the model approaches the General Relativity limit of Barber's second self-creation theory. Using Eq. (18), the effective gravitational coupling term in the field equations can be written as

$$\frac{8\pi}{\Phi} = \frac{n(n+1)\beta^2}{2c_1\pi} \quad (24)$$

Substituting this result into the self-creation field equation gives

$$R_{ij} - \frac{1}{2}g_{ij}R = - \left(\frac{n(n+1)\beta^2}{2c_1\pi} \right) T_{ij} \quad (25)$$

This form clearly indicates that the field equations reduce to Einstein-type equations with an effective constant gravitational coupling. Hence, the obtained model does not provide an independent dynamical self-creation solution but instead corresponds to the General Relativity limit of the theory. Another important result of the model is the simple form of the total energy density given in Eq. (20). This relation shows that the sum of the matter energy density and the Rényi holographic dark energy density evolves inversely with time t . For positive values of c_1 and α , the total energy density decreases with cosmic time. This behavior is consistent with an expanding cosmological model, since the total energy

density is expected to decrease as the universe expands. Equation (19) further shows that the matter energy density is determined by the difference between the total energy density and the Rényi holographic dark energy density. Thus, the matter and dark energy components are directly related through the obtained exact solutions.

The pressure given in Eq. (21) depends on the model parameters n , c_1 , α and β . Therefore, both the higher-dimensional structure and the adopted Hubble parametrization directly influence the pressure behavior of the Rényi holographic dark energy component. The equation-of-state parameter given in Eq. (23) provides an important diagnostic for interpreting the dark energy behavior of the model. Since $\omega = p/\rho_r$, its evolution can indicate whether the model exhibits quintessence-like, cosmological-constant-like, or phantom-like behavior (Copeland, 2006). In order to investigate the graphical behavior of the obtained cosmological quantities, the values of α and β , which determine the Hubble parametrization, are chosen in accordance with observational data sets commonly used in Rényi holographic dark energy models. The remaining parameters, namely s , η , c_1 , and n , are fixed to obtain physically acceptable and illustrative cosmological behavior within the framework of the present higher-dimensional model. The numerical values used in the graphical analysis are presented in Table 1.

Table 1. Numerical values of the model parameters used for graphical analysis

Data Set	α	β	s	η	c_1	n
SN Ia (Cunha, 2009)	1.0	0.4814	5	1.4	1	3
SN Ia + H(z) + BAO/CMB (Santos et al., 2016)	1.6	0.2770	12	1.4	1	3
SN Ia + BAO + H(z) (Xu & Lu, 2009)	1.3	0.3762	8	1.4	1	3
CC + SN Ia + BAO + R18 (Haridasu, 2018)	1.6	0.2963	10	1.4	1	3

Using the parameter values listed in Table 1, the graphical evolution of the cosmological quantities is analyzed. The parameter n determines the dimensionality of the spacetime through $D = n + 2$. In the graphical analysis, $n = 3$ is adopted, corresponding to a five-dimensional spacetime and representing the simplest higher-dimensional extension beyond the standard four-dimensional ($n = 2$) case. The scale factor A , matter energy density ρ_m , Rényi holographic dark energy density ρ_r , pressure p , and equation of state parameter ω are examined as functions of cosmic time. Although $n = 3$ is adopted to illustrate the higher-dimensional scenario, the four-dimensional case is directly recovered by setting $n = 2$. The analytical solutions show that changing the dimensionality does not alter the overall physical behavior of the model. In particular, the scale factor and the energy densities preserve the same evolution, while the dimensional dependence appearing in the remaining quantities affects their numerical values rather than the general cosmological behavior. Thus, the higher-dimensional

formulation provides a generalization of the model, with the standard four-dimensional case contained as a particular limit.

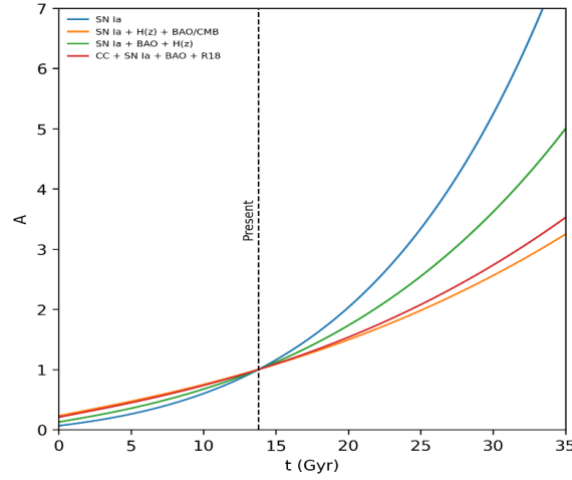


Figure 1. Evolution of the scale factor A versus cosmic time t for different observational data sets.

Figure 1 illustrates the evolution of the scale factor (A) with respect to cosmic time (t) for the different observational data sets. The scale factor is normalized to $A=1$ at the present cosmic time ($t=13.8$) Gyr. It increases monotonically for all data sets, indicating an expanding universe. Among the considered cases, the SN Ia data set yields the most rapid expansion, whereas the SN Ia + H(z) + BAO/CMB data set gives the slowest expansion. Following the analysis of the scale factor, the evolution of the matter energy density is examined using Eq. (19), and the corresponding behavior of ρ_m is shown in Figure 2.

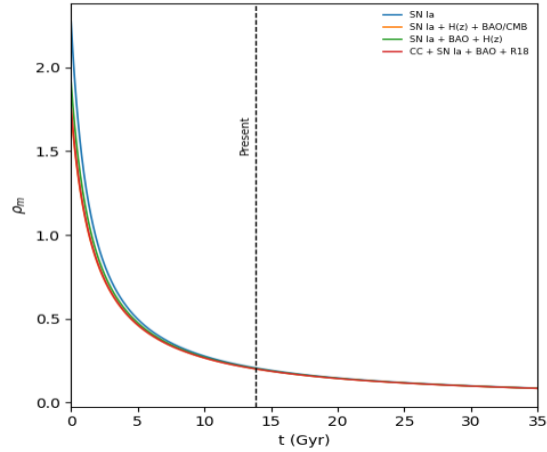


Figure 2. Evolution of the matter energy density ρ_m versus cosmic time t for different observational data sets.

Figure 2 shows that the matter energy density ρ_m decreases with cosmic time for all observational data sets. This behavior is consistent with an expanding universe, since the matter content becomes diluted as the universe evolves. The curves exhibit similar decreasing trends and approach small positive values at late times. This result indicates that the contribution of matter becomes progressively less dominant

during the cosmic evolution of the model. The evolution of the Rényi holographic dark energy density is obtained from Eq. (15), and its behavior for the different observational data sets is shown in Figure 3.

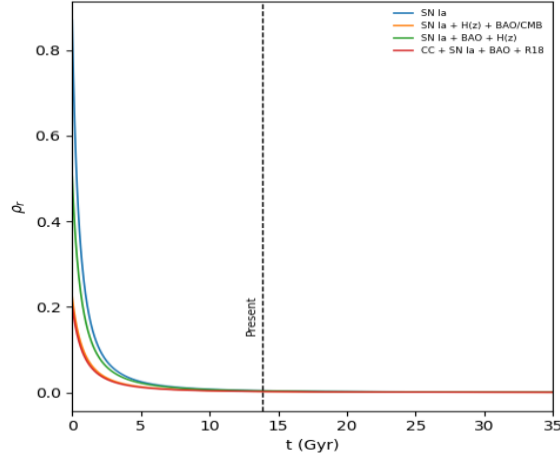


Figure 3. Evolution of the Rényi holographic dark energy density ρ_r versus cosmic time t for different observational data sets.

Figure 3 shows that ρ_r decreases rapidly at early cosmic times and approaches very small positive values at late times for all data sets. This behavior follows from the time dependence of ρ_r in Eq. (15) and indicates that the Rényi holographic dark energy density decreases as cosmic time increases. The pressure of the Rényi holographic dark energy component is obtained from the corresponding field equations, and its evolution is presented in Figure 4.

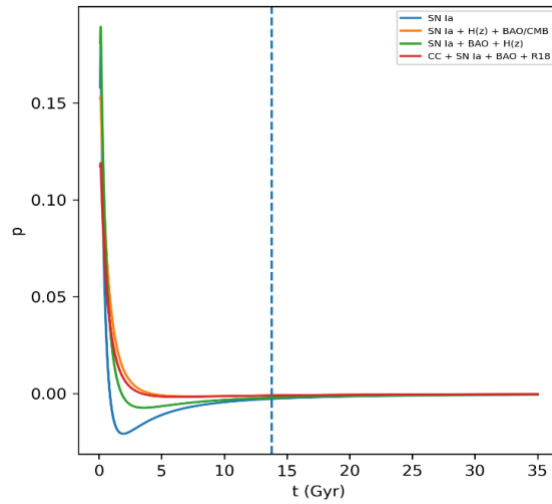


Figure 4. Evolution of the pressure p versus cosmic time t for different observational data sets.

Figure 4 shows that the pressure (p) decreases rapidly at early cosmic times and tends toward zero at late times for all observational data sets. At early times, the pressure takes both positive and slightly negative values depending on the data set, whereas at later times it stabilizes near zero. This behavior indicates that the dark energy component evolves dynamically, with its pressure gradually approaching zero at late cosmic times. The equation of state (EoS) parameter is defined as $\omega = \frac{p}{\rho_r}$. Using the obtained

expressions for pressure and Rényi HDE density, the evolution of ω for different observational data sets is shown in Figure 5.

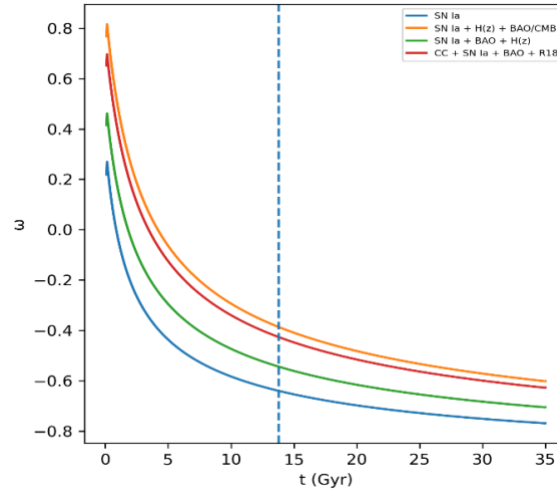


Figure 5. Evolution of the EoS parameter ω versus cosmic time t for different observational data sets.

Figure 5 shows that the EoS parameter decreases with cosmic time for all data sets. At early times, ω takes positive values, corresponding to a non-dark-energy-dominated phase. As cosmic time increases, ω becomes negative and approaches values between -1 and 0 , corresponding to quintessence-like behavior. None of the curves cross the $\omega = -1$ boundary, indicating that the model does not enter the phantom regime. Therefore, the model describes a dynamical dark energy scenario that remains within the quintessence region at late times.

Overall, the obtained results indicate that the model provides a consistent description of cosmic evolution within the framework of self-creation cosmology. In particular, the scalar field is found to be constant, implying that the field equations effectively reduce to a form equivalent to General Relativity with a modified coupling term. Despite this reduction, the inclusion of Rényi holographic dark energy leads to a viable cosmological scenario in which the equation-of-state parameter remains within the quintessence region. Thus, the model successfully describes the late-time accelerated expansion of the universe without entering the phantom regime.

CONCLUSION

In this study, a higher-dimensional flat FRW cosmological model filled with pressureless matter and Rényi holographic dark energy has been investigated within the framework of self-creation cosmology. By adopting a specific parametrization of the Hubble parameter, exact analytical solutions of the field equations have been obtained, and the cosmological dynamics of the model have been systematically analyzed.

The obtained results demonstrate that the model successfully describes an expanding universe with a dynamically evolving dark energy component. In particular, the equation-of-state parameter

evolves from positive values at early times to negative values at late times and remains within the quintessence region. This behavior indicates that the model provides a physically consistent description of the late-time accelerated expansion of the universe without entering the phantom domain.

One of the most significant findings of this study is that the self-creation scalar field reduces to a constant. This result implies that the field equations effectively reduce to a form equivalent to General Relativity with a modified coupling term, indicating that the model does not yield an independent dynamical self-creation solution. This outcome is in direct agreement with the non-existence results reported in the literature, according to which no non-trivial deviations from General Relativity arise under similar conditions.

Despite this reduction, the inclusion of Rényi holographic dark energy leads to a physically viable and observationally motivated cosmological scenario. In this respect, the model provides a consistent framework that both clarifies the limitations of self-creation cosmology and highlights the role of alternative dark energy formulations.

Furthermore, the results obtained in this study provide a useful basis for future investigations involving alternative Hubble parametrizations and different entropy-based dark energy models within the self-creation framework. The model may also be extended through more detailed comparisons with observational data, thereby providing further insight into its theoretical and observational viability.

Author Contribution

The author contributed 100% to the study and was responsible for the conceptualization, development of the theoretical framework, mathematical calculations, analysis and interpretation of the results, literature review, preparation of the figures, and writing and revision of the manuscript.

Funding Information

This study was not funded by any institution or organization. No financial support, grant, project funding, or commercial assistance was received for the research, authorship, or publication of this article.

Artificial Intelligence Statement

Generative artificial intelligence tools were used solely for language editing, grammatical improvement, and enhancement of the readability of the manuscript. Artificial intelligence was not used to generate the theoretical model, mathematical derivations, scientific results, figures, or conclusions of the study. All AI-assisted revisions were critically reviewed and verified by the author, who takes full responsibility for the accuracy, originality, and integrity of the final manuscript.

Conflict of Interest Statement

The author declares that there is no conflict of interest regarding the publication of this study.

Ethical Statement

This study is theoretical in nature and does not involve human participants, animals, personal data, or experimental procedures requiring ethics committee approval. Therefore, ethics committee approval was not required. The author declares that all processes of this study were conducted in accordance with the principles of the Pen Academic Publishing Research Ethics Policy.

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