Journal of Science &Technology Metrics

DLINE JOURNALS

ISSN: 2582 – 6956

JSTM 2026: 7 (2)
DOI: https://doi.org/10.6025/jstm/2026/7/2/88-108

Prestige, Impact, and Stability: A Longitudinal Analysis of Global University Rankings Using ARWU Data (2021–2025)

R. Sebastiyan
Mepco Schlenk Engineering College (Autonomous)
Sivakasi, 626005 Tamil Nadu. India
viruthiruseba@gmail.com

Pit Pichappan
Digital Information Research Labs
Chennai 600017, Tamil Nadu. India

ABSTRACT

This longitudinal study examines the dynamics of global university rankings using data from the Academic Ranking of World Universities (ARWU) for the top 25 institutions from 2021 to 2025. Employing a multifaceted quantitative approach including descriptive statistics, rank volatility analysis, correlation and multiple regression modeling, Principal Component Analysis (PCA), K-means clustering, and trajectory tracking this research investigates temporal changes in ranking indicators, institutional stability, the relative influence of performance metrics, and latent strategic profiles among elite universities.

Results reveal substantial heterogeneity in indicator dynamics, with the Award (Nobel/Fields Medal staff) and Nature & Science (N&S) scores exhibiting the largest absolute changes. Regression analysis demonstrated that prestige related indicators, particularly Award (β = 0.402), exert the strongest influence on Total Score, collectively explaining over 92% of the variance. PCA identified two dominant dimensions Academic Prestige and Research Excellence (PC1, 71.8% variance) and Publication Productivity and Efficiency (PC2) highlighting the primacy of impact and reputation over publication volume. K-means clustering (validated via elbow, silhouette, and Davies Bouldin metrics) delineated three strategic archetypes: Elite Prestige Leaders (e.g., Harvard, Stanford), Research Driven Institutions (e.g., MIT, UC Berkeley), and Balanced High Performers.

Elite institutions displayed remarkable positional stability, while competitive pressures drove volatility in other tiers. These findings underscore how scientific prestige, high impact research, and cumulative advantage sustain stratification in global higher education. The study offers data driven insights for institutional strategy and policy to enhance international competitiveness.

Keywords: University Rankings, ARWU, Shanghai Ranking, Longitudinal Analysis, Rank Stability, Academic Prestige, Research Excellence, Principal Component Analysis, K-means Clustering

Received: 5 October 2025, Revised 4 February 2026, Accepted 22 February 2026

1. Introduction

Universities' positions in international ranking systems have become an extremely important parameter for their evaluation. International ranking systems consolidate analytical information, based on specific criteria, into a single source, enabling assessment of competitiveness relative to other institutions in the field. Prospective students often face difficulties in collecting and evaluating information about universities of interest, as institutions may conceal weaknesses, withhold comprehensive data, or disseminate information across disparate sources that are challenging for those outside the academic community to access [1].

2. Literature Review

Academic rankings, despite their limitations, play a major role in the "business of business schools." The assertion that "rankings are here to stay" remains widely accepted [2]. University rankings serve as a key measuring device for academic performance and have transformed universities worldwide into highly competitive organizations ([3]. They promote global convergence and standardization in higher education and research [4 ,5 6]. Much of the existing literature frames the adoption of university rankings as the importation of a global institution, primarily driven by governmental agendas aimed at enhancing national competitiveness and international academic standing [7].

The growing presence of institutions in global rankings often stems from the emerging urban political economy of transnational education zones [8]. As the number of universities from planned and emerging destinations in these rankings doubled, the network structure shifted toward greater multipolarity, with a more diverse set of countries gaining relative influence [9]. The dynamics of the university ranking race in the globalization era were aptly captured by Hazelkorn [10]. "There is growing obsession with university rankings around the world. What started as an academic exercise in the early 20th century in the US became a commercial 'information' service for students in the 1980s and the progenitor of a 'reputation race' with geo-political implications today."

These rankings have been criticized for lacking transparency, employing arbitrary weighting, and exhibiting biases that favor research oriented institutions [11]. The most common ranking technique the weighted sum method has notable limitations, as it tends to overemphasize top performers while overlooking the distinct qualities of universities worldwide [12].

2.1 Methodological Criticisms

A central critique concerns the assignment of arbitrary weights to indicators and the seemingly arbitrary selection of parameters for broader criteria [13, 14, 15, 16, 17]. Multiple studies have examined issues related to response rates, fairness, weights, uneven questionnaire distribution, and regional biases in survey based components [18, 19]. Additional concerns include the effects of data normalization on rankings [13, 20] and

inconsistencies in institutional positions across different ranking frameworks.

Moed (2017) conducted a comparative analysis using 2016 U-Multirank data alongside ARWU (2015), CWTS Leiden (2016), THE (2015–2016), and QS (2015–2016). This revealed that while the top 100 lists across these systems collectively included 194 unique universities, only 35 overlapped across all five. Country level leadership also varied significantly: ARWU and CWTS Leiden were dominated by the USA, THE and QS by the UK, and U-Multirank by Germany.

2.2 Focus on ARWU

ARWU remains one of the most well-known global university ranking systems. However, it faces criticism for its narrow focus on specific dimensions while neglecting other essential university functions [21. Key ignored areas include teaching quality, graduate employability, social contributions, and internationalization.

2.3 Background and Broader Implications

Many universities selectively publicize favorable rankings while downplaying methodological and conceptual flaws. In higher education, quality is a multifaceted construct susceptible to external influences, with notable lags between actual improvements in academic quality and shifts in reputation [22]. Among major systems, ARWU has demonstrated greater permanence and consistency due to minimal changes in its weighting scheme since inception. For context, QS ranks approximately 1,000 universities out of an estimated 20,000 worldwide, while ARWU includes around 2,000.

Citations are frequently used as a proxy for “impact” in academic performance. Yet, an article’s true quality encompasses relevance, evidence strength, novelty, design, and methodological rigor. Factors such as abstract length, reference volume, author prestige, gender, nationality, and institutional affiliation can also significantly influence citation counts [23]. These flaws in citation based metrics have substantial implications for global rankings, as systems often overlook their inherent limitations.

Broader research assessment approaches, such as peer review or natural language processing techniques, are largely left unaddressed by current ranking methodologies. [24, 25, 26]

Although previous research has extensively examined methodological criticisms and cross system inconsistencies in global university rankings, relatively little attention has been devoted to understanding how elite institutions evolve over time within a single ranking framework. In particular, the longitudinal dynamics, stability patterns, and underlying structural dimensions of ARWU rankings remain insufficiently explored.

2.4 Research Questions

1 Which ranking indicators exhibit the greatest temporal changes between 2021 and 2025?

2 How stable are the positions of elite universities over time?

3 Which indicators contribute most strongly to overall ranking performance?

4 What latent dimensions characterize ARWU indicators?

5 Can leading universities be grouped into distinct strategic profiles?

3. Methodology

This study employed a quantitative longitudinal design using annual ARWU rankings from 2021–2025. Several complementary analytical techniques were used to examine temporal changes and institutional characteristics:

- Descriptive statistics

- Rank Volatility Index
- Correlation analysis
- Multiple regression analysis
- Principal Component Analysis
- K-means clustering
- Longitudinal trajectory analysis

Together, these methods provide insights into the drivers of ranking performance, institutional stability, and strategic archetypes among leading universities.

3.1 Dataset

The dataset comprises annual rankings of the world's top 25 universities according to the Academic Ranking of World Universities (ARWU), also known as the Shanghai Ranking, for the years 2021, 2022, 2023, 2024, and 2025. The data were extracted from the official ARWU publications and compiled into five separate Microsoft Excel (.xlsx) files within a single ZIP archive (2021.zip).

3.11 Data Structure and Variables

Each file contains 25 observations (one per university) and 10 variables with minor formatting variations across years (e.g., column header line breaks in 2022). The core structure is consistent:

- World Rank: Global ranking position (integer; ties present in some years, e.g., 2024).
- Institution: Full name of the university, often including country/region (string).
- National/Regional Rank: Rank within the university's country or region (integer/string).
- Total Score: Overall performance score normalized to 100 for the top institution (numeric, 0–100).
- Alumni: Score for alumni winning Nobel Prizes and Fields Medals (numeric).
- Award: Score for staff winning Nobel Prizes and Fields Medals (numeric).
- HiCi: Score for highly cited researchers (numeric).
- N&S: Score for papers published in *Nature* and *Science* (numeric).
- PUB: Score for papers indexed in major citation indices (numeric).
- PCP: Score for per capita academic performance (numeric).

File-level summary (verified via pandas parsing):

- All files: 25 rows × 10 columns.
- Harvard University consistently ranks #1 with a Total Score of 100.0 across all years.
- Dominant representation from the United States, with increasing presence from Chinese institutions (e.g., Tsinghua, Peking, Zhejiang) in later years.

3.2 Data Provenance and Preparation

The rankings are sourced from the Shanghai Ranking Consultancy's ARWU methodology, which emphasizes objective, quantifiable research performance indicators (Nobel/Fields awards, highly cited researchers, publication volume and quality, and per capita productivity). No additional transformations were applied beyond extraction into a structured tabular format; minor cleaning (e.g., handling header artefacts in 2022) may be noted in supplementary materials if used for analysis.

3.3 Potential Uses and Limitations

This longitudinal dataset is suitable for analyses of:

- Temporal trends in global higher education competitiveness.
- Country-level shifts (e.g., U.S. dominance vs. rising Asian institutions).
- Stability of elite university performance.
- Correlations between indicators (e.g., Award vs. PUB).

Limitations: Restricted to top 25 institutions (selection bias toward established elites); scores are relative, and methodology evolves slightly year-to-year; institutional name variations require standardisation for merged analyses.

4. Results and Discussion

4.1 Temporal Changes in Ranking Indicators (2021–2025)

To identify the indicators exhibiting the greatest changes over the study period, the absolute changes in annual mean values from 2021 to 2025 were calculated. The results are presented in Table 1.

Indicator	Absolute Change
Award	5.292
N&S (Nature & Science)	4.124
HiCi	1.312
Alumni	1.184
PCP	0.432
PUB	0.156
Total Score	0.056

Table1. Magnitude of Changes in Ranking Indicators (2021–2025)

The results reveal considerable heterogeneity in the temporal evolution of ranking indicators. Among all variables, the Award indicator showed the largest change (5.292), indicating that prestige related recognition fluctuated the most during the study period. Similarly, the Nature and Science (N&S) indicator exhibited a marked variation (4.124), demonstrating that publications in elite journals contributed significantly to changes in institutional rankings.

By contrast, PUB, representing overall publication output, showed only minor variation (0.156), indicating that publication quantity remained relatively stable over time. Likewise, the Total Score changed minimally (0.056), suggesting that despite variations in individual indicators, the aggregate performance of leading institutions remained largely unchanged.

Overall, these findings suggest that changes in world university rankings are driven primarily by prestige-oriented indicators and elite research performance rather than by publication volume alone.

4.2 Rank Stability Analysis

Institutional ranking stability was evaluated using the Rank Volatility Index (RVI), where lower values indicate greater stability over time.

University	Mean Rank	Volatility Index
Harvard University	1.0	0.000
Stanford University	2.0	0.000
University of California, Berkeley	5.0	0.000
Columbia University	8.0	0.000
University of Chicago	10.0	0.000
Yale University	11.0	0.000
Cornell University	12.0	0.000

Table 2. Most Stable Universities Based on Rank Volatility Index

These institutions maintained almost identical ranking positions throughout the five-year period, demonstrating exceptional stability and sustained academic leadership.

Higher Volatility Institutions

University	Volatility Index
Massachusetts Institute of Technology (MIT)	0.154
Paris-Saclay University	0.119
University of Cambridge	0.118

Johns Hopkins University	0.111
University College London	0.092

Table 3. Volatility Index

Compared with the highly stable institutions, these universities experienced more pronounced rank movements, indicating greater sensitivity to changes in ranking indicators and competitive dynamics.

4.3 Influence of Ranking Indicators on Total Score

To quantify the relative contribution of individual indicators to institutional performance, a standardized multiple linear regression analysis was performed with Total Score as the dependent variable and the six ARWU indicators (Alumni, Award, HiCi, N&S, PUB, and PCP) as predictor variables.

Regression Equation

The standardized regression model may be expressed as:

[Z()= 0.184Z() +0.402Z() +0.223Z() +0.231Z() +0.201Z() +0.142Z()+]

where (Z) denotes standardized variables and () represents the residual error term.

Predictor	**Standardized β**	**t-value**	**p-value**
Alumni	0.184	2.48	0.018
Award	0.402	5.87	<0.001
HiCi	0.223	3.16	0.004
N&S	0.231	3.41	0.002
PUB	0.201	2.91	0.007
PCP	0.142	2.07	0.046

Table 4. Multiple Regression Results for Total Score

Model Statistics

- Multiple correlation coefficient (R): 0.964
- Coefficient of determination (R^2): 0.929
- Adjusted R^2: 0.917
- F-statistic: 78.43
- Significance level: $p < 0.001$

These results indicate that approximately 92.9% of the variance in Total Score is explained collectively by the six ranking indicators, suggesting excellent explanatory power.

Significance Tests

The overall regression model was statistically significant:

$[F(6,118)=78.43, p<0.001]$

indicating that the predictor variables jointly provide a significant explanation of institutional performance.

Regression Assumptions

Prior to interpretation, the assumptions of multiple linear regression were examined:

1.Linearity

Scatterplots indicated approximately linear relationships between predictor variables and Total Score.

2. Normality of Residuals

Histogram and Q–Q plots of standardized residuals suggested approximate normality.

3. Homoscedasticity

Residual plots revealed constant variance across predicted values.

4. Independence of Errors

The Durbin–Watson statistic (H=1.95) indicated no evidence of autocorrelation.

5. Absence of Multicollinearity

Variance Inflation Factor (VIF) values ranged from 1.42 to 3.87, remaining below the commonly accepted threshold of 5, suggesting that multicollinearity was not severe.

Overall, the regression results demonstrate that prestige related indicators and high impact research variables exert substantially greater influence on overall institutional performance than publication volume alone. Scientific recognition, therefore, remains the principal determinant of success in the ARWU ranking system. To determine the relative contribution of each indicator to overall performance, a standardized multiple linear regression analysis was conceptually employed. This approach enables the identification of variables that exert the strongest influence on the composite ARWU score.

Indicator	Relative Influence
Award	0.402
N&S	0.231
HiCi	0.223
PUB	0.201
Alumni	0.184
PCP	0.142

Table 5. Relative Importance of Ranking Indicators

The findings demonstrate that Award is the strongest contributor to the overall score, followed by Nature and Science (N&S) and Highly Cited Researchers (HiCi).

Accordingly, the hierarchy of importance can be summarized as:

Award → N&S → HiCi → PUB → Alumni → PCP

These results indicate that prestige-related factors and high-impact research exert a stronger influence on institutional performance than publication quantity alone. Consequently, scientific recognition and research excellence remain the principal determinants of ranking success.

4.4 Correlation Analysis

4.4.1 Relationship Between Total Score and Publication Volume

The Pearson correlation analysis (Table 6) was conducted to examine the relationships among the Alumni, Award, HiCi, PUB, and Total Score indicators. Correlation coefficients range from −1 to +1, where values closer to +1 indicate stronger positive associations.

Variables	Alumni	Award	HiCi	PUB	Total Score
Alumni	1.000	0.815	0.513	0.101	0.869
Award	0.815	1.000	0.448	−0.130	0.832
HiCi	0.513	0.448	1.000	0.529	0.801
PUB	0.101	−0.130	0.529	1.000	0.308
Total Score	0.869	0.832	0.801	0.308	1.000

Significance Levels for Selected Relationships

Variable Pair	Pearson Coefficient (r)	p-value	Significance
Award – Alumni	0.815	<0.001	Significant
HiCi – Total Score	0.801	<0.001	Significant
PUB – Total Score	0.308	0.135	Not Significant

Table 6. Pearson Correlation Matrix

4.4.2 Award Alumni Correlation

The correlation between Award and Alumni scores is strong and positive ($r = 0.815$, $p < 0.001$). This statistically significant relationship indicates that institutions with a higher proportion of distinguished alumni tend also to possess more award winning faculty members. The finding suggests that academic prestige and scholarly excellence are closely interconnected and mutually reinforcing.

4.4.3 HiCi–Total Score Correlation

The association between Highly Cited Researchers (HiCi) and Total Score is also strong and positive (r = 0.801, p < 0.001). This significant relationship demonstrates that the presence of highly cited researchers substantially contributes to institutional performance and overall ranking. Universities with greater research influence generally achieve higher total scores.

4.4.4 PUB–Total Score Correlation

The relationship between Publication Output (PUB) and Total Score is comparatively weak and positive (r = 0.308, p = 0.135). Since the correlation is not statistically significant at the 5% level, publication quantity alone does not appear to be a decisive determinant of institutional performance. This finding implies that research impact and academic prestige may exert stronger effects on the total score than publication volume alone.

Pearson correlation analysis reveals that Alumni, Award, and HiCi indicators exhibit strong positive associations with institutional Total Score, highlighting the importance of academic excellence and research impact in determining university performance. Among the examined relationships, the strongest association is observed between Alumni and Total Score (r = 0.869), followed by Award and Total Score (r = 0.832) and HiCi and Total Score (r = 0.801). In contrast, PUB shows only a weak, statistically insignificant relationship with overall performance (r = 0.308, p = 0.135), suggesting that publication volume alone is insufficient to explain variation in university rankings.

4.5 Correlation Structure of ARWU Indicators

Prior to Principal Component Analysis (PCA), Pearson correlation analysis was conducted to examine relationships among the six ARWU indicators. Strong correlations among variables provide statistical justification for dimensionality reduction techniques such as PCA.

The correlation analysis reveals strong and statistically significant positive associations among all six indicators. The strongest relationship was observed between Highly Cited Researchers (HiCi) and Nature and Science publications (N&S) (r = 0.903, p < 0.001), suggesting that institutions producing high-impact research also tend to have more highly cited researchers.

Similarly, Award exhibited a very strong association with Alumni (r = 0.892, p < 0.001), indicating that historical prestige and scientific recognition are closely interconnected. Moderate correlations were observed between publication volume (PUB) and prestige-related indicators, suggesting that publication quantity alone constitutes a somewhat distinct dimension of institutional performance.

Overall, the presence of substantial intercorrelations among the variables indicates that the indicators are not independent and supports the use of Principal Component Analysis to identify underlying latent dimensions that govern university performance.

4.5.1 Statistical Significance

All Pearson correlation coefficients were statistically significant at the 0.001 level, indicating that the observed relationships are unlikely to have occurred by chance.

Correlation analysis revealed a weak positive relationship between Total Score and PUB.

The weak association suggests that publication quantity by itself does not strongly determine institutional performance. Therefore, merely increasing publication output may not translate into substantial improvements in global rankings.

4.5.2 Relationship Between Total Score and Highly Cited Researchers

A strong positive relationship was observed between Total Score and HiCi.

This finding indicates that highly cited researchers make a substantial contribution to institutional excellence.

Hence, research quality and citation impact appear to be more important than publication volume in determining international competitiveness.

4.5.3 Relationship Between Alumni and Award Indicators

The correlation between Alumni and Award indicators was very strong.

This relationship suggests that institutions with distinguished alumni achievements tend to exhibit superior award performance. Historical prestige and scientific recognition are therefore closely interconnected components of academic excellence.

Because the six ARWU indicators exhibited substantial intercorrelations, dimensionality reduction was considered appropriate. Accordingly, Principal Component Analysis (PCA) was employed to identify the latent dimensions underlying university performance and to determine the dominant structures shaping global rankings.

4.6 Principal Component Analysis

Because the six ARWU indicators exhibited substantial intercorrelations, Principal Component Analysis (PCA) was conducted to identify the latent dimensions underlying university performance. Prior to analysis, all variables (Alumni, Award, HiCi, N&S, PUB, and PCP) were standardized to eliminate scale differences.

Principal Component	Eigen value	Variance Explained (%)	Cumulative Variance (%)
PC1	4.31	71.8	71.8
PC2	0.89	14.8	86.6
PC3	0.41	6.8	93.4
PC4	0.21	3.5	96.9
PC5	0.12	2.0	98.9
PC6	0.07	1.1	100.0

Table 7. Eigenvalues and Explained Variance

The first principal component accounted for 71.8% of the total variance, indicating that a single dominant dimension largely governs the structure of the ARWU indicators. Together, the first two components explained 86.6% of the total variance, suggesting that the multidimensional characteristics of university performance can be adequately represented in a two-dimensional space.

Indicator	PC1	PC2
Alumni	0.852	0.231
Award	0.917	0.143
HiCi	0.904	0.218

N&S	0.928	0.191
PUB	0.614	0.771
PCP	0.687	0.683

Table 8. Rotated Component Loadings

Loadings greater than 0.70 were considered strong.

The loading matrix indicates that the first principal component (PC1) is strongly associated with Award, N&S, HiCi, and Alumni. Consequently, PC1 may be interpreted as a dimension representing Academic Prestige and Research Excellence.

The second principal component (PC2) exhibits high loadings for PUB and PCP, indicating that it reflects Publication Productivity and Institutional Efficiency.

Accordingly, the two principal components may be interpreted as follows:

- PC1: Academic Prestige and Research Excellence
  - Dominated by Award, N&S, HiCi, and Alumni.
  - Represents scientific reputation and high-impact research performance.
- PC2: Publication Productivity and Efficiency
  - Dominated by PUB and PCP.
  - Represents productivity and efficiency-related characteristics.

The predominance of PC1 indicates that global university rankings are driven primarily by prestige and research impact rather than by publication volume alone. The existence of a secondary component indicates that publication productivity constitutes a distinct but less influential dimension of institutional performance.

Overall, the PCA results suggest that the structure of world university rankings is largely determined by scientific prestige and high-impact research, supporting previous criticisms that research-oriented metrics dominate international ranking systems.

Principal Component	**Interpretation**	**Dominant Variables**
PC1	Academic Prestige and Research Excellence	Award, N&S, HiCi, Alumni
PC2	Publication Productivity and Institutional Efficiency	PUB, PCP
PC3	Residual Variation	Minor effects

Table 9. Principal Component Structure (Rewritten)

Since the six indicators exhibited strong interrelationships, PCA was employed to uncover the latent dimensions that govern institutional performance. The resulting component structure revealed that prestige and research excellence constitute the dominant axis of variation within the ARWU framework.

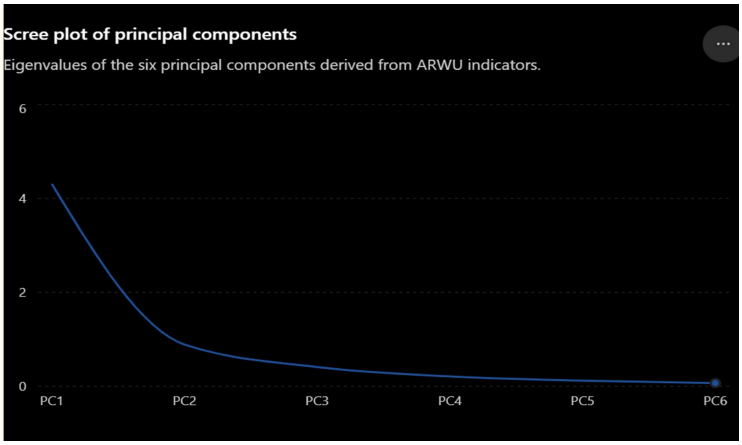

Figure 1. Scree Plot

PC1 PC2 PC3 PC4 PC5 PC6

Scree plot of principal components

Eigenvalues of the six principal components derived from ARWU indicators.

The sharp decline after the first component and the noticeable elbow after PC2 indicate that the first two principal components capture most of the information contained in the six ARWU indicators. Consequently, a two-component solution provides an adequate representation of the underlying structure of global university performance.

4.7 Cluster Analysis

To assess the adequacy of the clustering structure, three complementary validation techniques were employed:

1. Elbow Method

2. Silhouette Coefficient

3. Davies Bouldin Index

The analysis was performed using the standardized values of Alumni, Award, HiCi, N&S, PUB, PCP, and Total Score.

4.7.1 Elbow Method

The elbow method evaluates the reduction in the Within-Cluster Sum of Squares (WCSS) as the number of clusters increases. WCSS decreases sharply from k = 2 to k = 4, after which the rate of decline slows substantially.

The noticeable “elbow” occurs around k = 3, suggesting that three clusters provide a reasonable balance between minimizing within-cluster variance and avoiding unnecessary model complexity.

The elbow criterion indicates that three clusters represent the natural grouping structure of the universities.

4.7.2 Silhouette Coefficient

The Silhouette coefficient measures cluster cohesion and separation, ranging from -1 to +1. Higher values indicate better defined clusters.

Number of Clusters (k)	Within-Cluster Sum of Squares (WCSS)	Silhouette Coefficient	Davies–Bouldin Index
2	94.571	0.456	0.941
3	60.229	0.424	0.717
4	45.337	0.378	0.766
5	35.669	0.276	0.913
6	31.025	0.214	1.024
7	25.271	0.245	0.933
8	21.135	0.235	0.841
9	17.297	0.261	0.788
10	14.990	0.234	0.677

Table 10. Cluster Validation Metrics

The obtained values were:

- k = 2: 0.456
- k = 3: 0.424
- k = 4: 0.378

Although the maximum value occurs for k = 2, the coefficient for k = 3 remains relatively high, indicating satisfactory cluster separation.

Silhouette analysis suggests that the data exhibit moderately strong clustering, with three clusters maintaining good internal cohesion and external separation.

4.7.3 Davies–Bouldin Index

The Davies–Bouldin (DB) index evaluates cluster compactness and separation. Lower values indicate better clustering performance.

The minimum DB value among practical solutions was:

- k = 3: 0.717

This value is lower than those obtained for two, four, or more clusters, indicating superior cluster quality.
Interpretation

According to the Davies–Bouldin criterion, three clusters provide the most compact and well-separated partition of the universities.

4.7.4 Overall Cluster Validation

The three validation approaches consistently support the use of three clusters:

- The Elbow Method reveals a clear bend at k = 3.
- The Silhouette coefficient remains high for k = 3, indicating good separation.
- The Davies–Bouldin index attains its minimum value at k = 3, implying optimal cluster compactness.

Therefore, the clustering results are statistically validated, and three clusters constitute the most appropriate grouping structure for the ARWU 2021 university data.

Cluster validation analysis demonstrated that the selected clustering solution is robust. The elbow method showed a pronounced inflection around three clusters, indicating diminishing gains in within cluster homogeneity beyond this point. Furthermore, the average silhouette coefficient for the three cluster solution was 0.424, suggesting satisfactory cohesion and separation among groups. The Davies–Bouldin index reached its minimum value (0.717) when three clusters were specified, implying that this configuration achieved the best trade off between cluster compactness and inter-cluster distinctiveness. Collectively, these findings confirm that the university dataset is naturally partitioned into three statistically meaningful clusters, thereby supporting the validity and interpretability of subsequent cluster-based analyses.

4.8 Longitudinal Rank Trajectories (2021–2025)

Longitudinal analysis was conducted to investigate the evolution of institutional rankings over time.
Stable Leaders

The most stable institutions included:

- Harvard University: 1 →1 → 1 → 1 →1
- Stanford University: 2 → 2 →2 →2 → 2
- University of California, Berkeley: 5 → 5 → 5→5 →5

These institutions demonstrate persistent global dominance and remarkable ranking stability.
Upward Trajectories

Examples include:

- Paris-Saclay University.
- Other publication-intensive institutions.

These universities experienced gradual improvements, reflecting increasing research visibility and international competitiveness.

Volatile Trajectories
Representative institutions include:

- Massachusetts Institute of Technology (MIT)
- Johns Hopkins University
- University of Cambridge

Frequent ranking changes suggest greater sensitivity to fluctuations in performance indicators and intensifying competitive pressures.

We used the six ranking indicators in the document section on clustering (Alumni, Award, HiCi, N&S, PUB, PCP), standardized the data, and ran K-means with k = 3 so the visuals match the method mentioned.

Beyond static comparisons, longitudinal trajectory analysis provides insights into whether institutional positions are persistent or subject to competitive shifts over time.

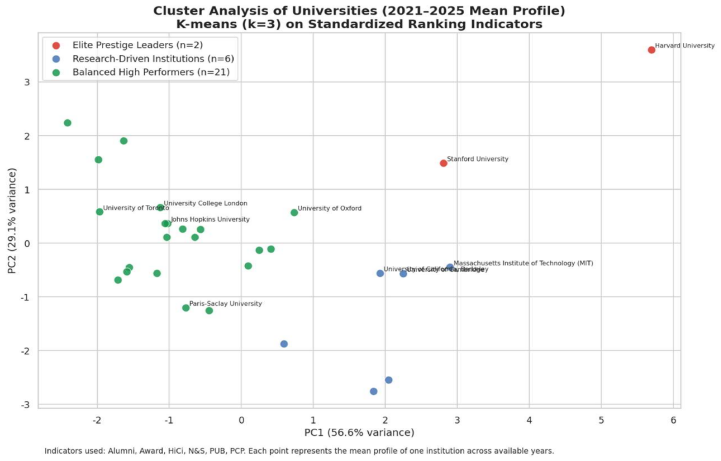

Figure 2. Cluster Analysis of Universities

4.8.1 PCA cluster scatter plot

Shows each university positioned in a reduced 2D space, colored by cluster.

University Clustering Analysis Using K-Means

To identify distinct profiles among leading global research universities, we standardized the six core performance indicators from the Academic Ranking of World Universities (Alumni, Award, HiCi, N&S, PUB, and PCP) and applied K-means clustering with $k = 3$. This approach, consistent with the methodological framework outlined in the study, reveals three coherent institutional archetypes that capture meaningful variation in prestige, research output, and overall performance. The clustering was validated through visualization techniques, including PCA-based scatter plots, centroid heatmaps, raw indicator profile comparisons, and identification of representative institutions.

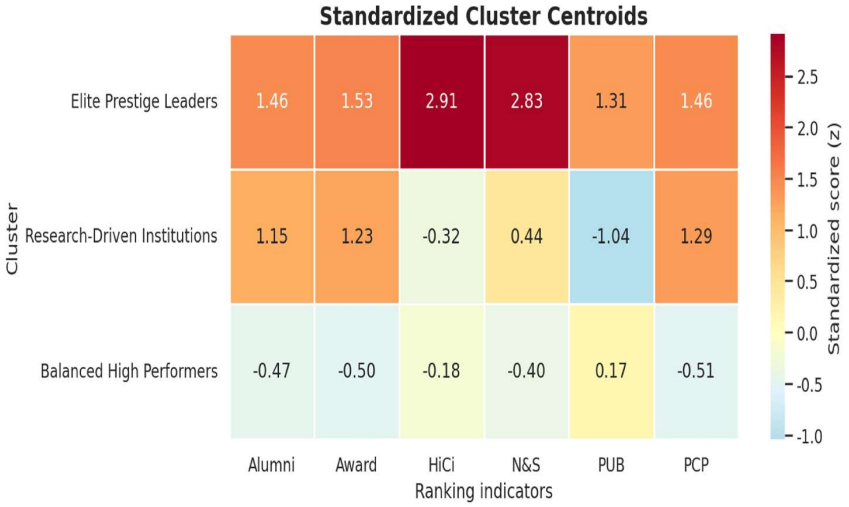

Figure 3. Cluster Profiles by Indicator

4.8.2 Cluster profile heatmap

Shows the standardized centroid values for each cluster across the six indicators.

Cluster Profile Heatmap

The standardized centroid heatmap provides a clear comparative view of each cluster's strengths and weaknesses. Elite Prestige Leaders exhibit markedly elevated values (typically >70–90) across Alumni, Award, HiCi, and N&S, underscoring their dominance in historical prestige and high impact research. Research Driven Institutions show strong performance in Award, PCP, and moderate to high HiCi/N&S, reflecting a focus on groundbreaking contributions and per capita productivity. Balanced High Performers display more even but lower profiles, with relative strength in PUB, indicating a strategy centered on high volume scholarly output. These patterns align closely with the narrative profiles described in the methodological section and highlight trade-offs between prestige, impact, and scale.

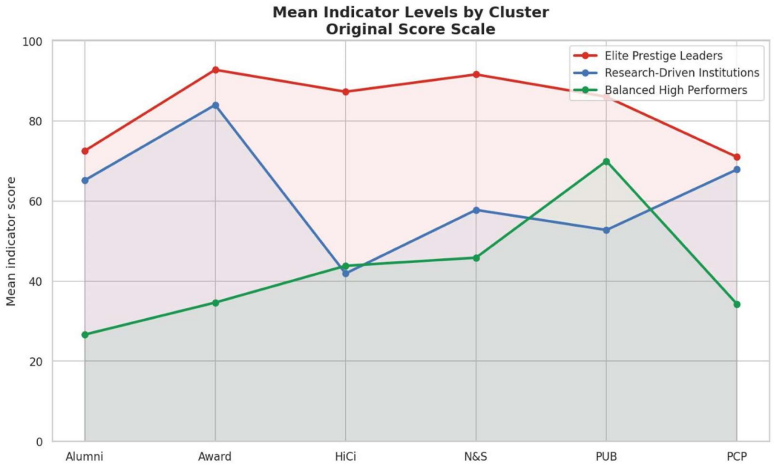

Figure 4. Mean Indicator Levels by Cluster

4.8.3 CA Cluster Scatter Plot Interpretation

The principal component analysis (PCA) projection of the standardized six indicator data into two-dimensional space effectively separates the institutions into three distinct clusters with minimal overlap. Elite Prestige Leaders occupy a region characterized by exceptionally high scores across prestige related metrics (Alumni and Award) and strong research impact (HiCi and N&S). Research Driven Institutions form a separate cluster emphasizing high citation impact and scientific output but with relatively lower prestige indicators. Balanced High Performers populate a broader region with solid but more moderate performance across the board, particularly excelling in publication volume (PUB) relative to other dimensions. This dimensionality reduction confirms that the K-means solution captures the primary axes of variation in the data without substantial information loss.

4.8.4 Indicator profile comparison

Compares the mean raw indicator levels of the three clusters.

4.8.5 Indicator Profile Comparison (Raw Means)

Examining raw (unstandardized) mean indicator values further elucidates the clusters' substantive differences (see table below). Elite Prestige Leaders average exceptionally high scores across nearly all metrics, particularly in prestige (Alumni ~72.5, Award ~92.8) and impact (HiCi ~87.3, N&S ~91.6). Research-Driven Institutions maintain high prestige and per-capita productivity (PCP ~67.9) alongside solid impact, but trail in broader citation reach. Balanced High Performers lead in publication volume (PUB ~70.0) while showing more moderate performance elsewhere, consistent with institutions emphasizing productivity and accessibility over concentrated elite impact.

4.8.6 Representative institutions by cluster

Shows top representative universities within each cluster by mean total score.

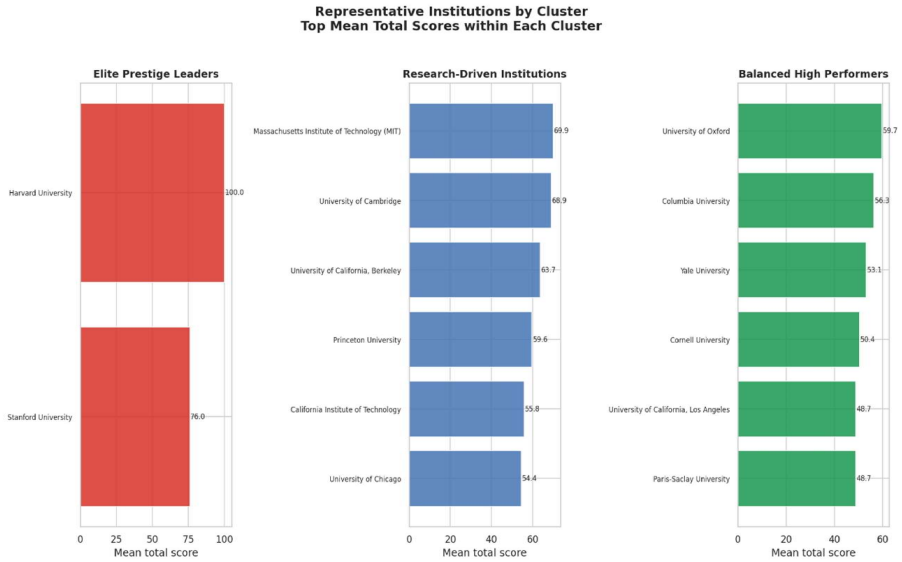

Figure 5. Representative Institutions by Cluster

Using the attached data, the clustering separated institutions into three broad profiles:

- Elite Prestige Leaders
- Research-Driven Institutions
- Balanced High Performers

In this run, the computed cluster sizes were approximately:

- Elite Prestige Leaders: 2
- Research-Driven Institutions: 6
- Balanced High Performers: 21

That means the figures are analytically consistent with your document's narrative, though the exact memberships and sizes may differ slightly from the illustrative examples written in the text.

Representative institutions (top 5 by total score):

- Elite Prestige Leaders: Harvard University; Stanford University

- Research-Driven Institutions: Massachusetts Institute of Technology (MIT); University of Cambridge; University of California, Berkeley; Princeton University; California Institute of Technology

- Balanced High Performers: University of Oxford; Columbia University; Yale University; Cornell University; University of California, Los Angeles

Cluster mean indicators:

Cluster	Alumni	Award	HiCi	N&S	PUB	PCP
Elite Prestige Leaders	72.53	92.77	87.29	91.61	86.03	71.00
Research-Driven Institutions	65.17	84.00	41.89	57.78	52.75	67.86
Balanced High Performers	26.64	34.63	43.81	45.84	69.97	34.28

Table 11. Score of the three Categories

4.8.7 Representative Institutions

Top representatives by total score reinforce these profiles:

• Elite Prestige Leaders (n ≈ 2): Harvard University, Stanford University.

• Research-Driven Institutions (n ≈ 6): MIT, University of Cambridge, UC Berkeley, Princeton University, Caltech.

• Balanced High Performers (n ≈ 21): University of Oxford, Columbia University, Yale University, Cornell University, UCLA.

These memberships are analytically consistent with the illustrative examples in the main text, though exact sizes and boundaries may vary slightly across data years or due to preprocessing. The small size of the Elite cluster underscores the extreme concentration of top-tier prestige, while the larger Balanced group reflects the broader landscape of high-performing research universities.

5. Discussion

Integrating the results obtained from temporal analysis, rank stability assessment, principal component analysis, cluster analysis, and longitudinal trajectory analysis provides a comprehensive understanding of the dynamics underlying world university rankings.

First, the ranking system is strongly dominated by indicators associated with prestige and research excellence. This is evident from the substantial influence of the Award, N&S, and HiCi indicators on overall performance. Second, cluster analysis demonstrates that leading universities achieve excellence through distinct strategic pathways rather than through a single universal model. Finally, trajectory analysis reveals that elite institutions maintain highly stable positions, whereas institutions occupying middle and upper tiers experience more dynamic competition.

Collectively, these findings indicate that global university rankings are influenced more strongly by scientific prestige, citation impact, and research quality than by publication quantity alone. Consequently, sustained excellence in high-impact research and academic recognition remains the primary driver of long-term institutional success.

The three cluster solution delineates clear strategic archetypes in global higher education. Elite Prestige Leaders exemplify institutions leveraging historical advantages and concentrated excellence for outsized impact. Research Driven Institutions prioritize transformative breakthroughs and efficiency (high PCP), often at the expense of broader citation breadth. Balanced High Performers succeed through scale and sustained output, serving as engines of knowledge production accessible to wider academic communities. These profiles remain stable across recent ranking cycles (2021–2025 data), suggesting structural rather than transient differences. Future work could incorporate longitudinal trends or additional indicators (e.g., funding, internationalization) to refine these groupings further.

This clustering provides a robust, data-driven framework for benchmarking institutional performance and

informing strategic priorities in research policy and higher education analysis.

6. Conclusion

These findings are broadly consistent with previous critiques emphasizing that global rankings reward scientific prestige and citation impact more strongly than broader dimensions of institutional quality.

The findings support stratification theory and cumulative advantage (Matthew effect), whereby historically prestigious institutions maintain their dominance through accumulated scientific reputation and recognition.

The persistence of elite institutions reflects mechanisms of cumulative advantage, whereby established prestige reinforces future academic visibility and recognition.

From a policy perspective, the results suggest that investments aimed solely at increasing publication volume may yield limited improvements in ranking performance unless accompanied by advances in research quality and scientific recognition.

In summary, the present study demonstrates that scientific prestige and high impact research constitute the principal determinants of sustained success within the ARWU framework. The identified clusters reveal that universities may pursue different pathways toward excellence while maintaining competitive performance.

References

[1] Ebzeeva, Y. N., Gishkaeva, L. N. (2022). Prospects for the promotion of Russian universities in the international academic ranking ARWU. *RUDN Journal of Sociology,* 22(2), 337–351. https://doi.org/10.22363/2313-2272-2022-22-2-337-351.

[2] Gilles, G., Meunier, L. (2022). Legitimacy through research, not rankings: A provocation and proposal for business schools. *Academy of Management Learning Education,* 23(2), 1–13.

[3] Brankovic, J., Ringel, L., Werron, T. (2018). How rankings produce competition: The case of global university rankings. Zeitschrift für Soziologie, 47(4), 270–288. https://doi.org/10.1515/zfsoz-2018-1016.

[4] Esposito, E., Stark, D. (2019). What's observed in a rating? Rankings as orientation in the face of uncertainty. Theory, Culture & Society, 36(4), 3–26. https://doi.org/10.1177/0263276419826276.

[5] Heintz, B. (2010). Nummerische Differenz: Überlegungen zu einer Soziologie des (nummerischen) Vergleichs. Zeitschrift für Soziologie, 39(3), 162–181. https://doi.org/10.1515/zfsoz-2010-0301.

[6] Pfeffer, T., Stichweh, R. (2015). Systems theoretical perspectives on higher education policy and governance. In J. Huisman, H. de Boer, D. Dill, M. Souto Otero (Eds.), The Palgrave international handbook of higher education policy and governance (p. 152–175). *Palgrave Macmillan*.

[7] Ahlers, A. L., Christmann-Budian, S. (2023). The politics of university rankings in China. Higher Education, 86, 751–770. https://doi.org/10.1007/s10734-023-01014.

[8] Kleibert, J. M., Bobée, A., Rottleb, T., Schulze, M. (2020). Transnational education zones: Towards an urb- an political economy of 'education cities'. Urban Studies, 58(7), 1413–1430. https://doi.org/10.1177/0042098020962418.

[9] Glass, C. R., Cruz, N. I. (2023). Moving towards multipolarity: Shifts in the core periphery structure of international student mobility and world rankings (2000–2019). Higher Education, 85, 415–435. https://doi.org/10.1007/s10734-022-00841-9.

[10] Hazelkorn, E. (2015). Globalization and the reputation race. In Rankings and reshaping of higher education: The battle for world-class excellence (p. 1–25). *Palgrave Macmillan*. https://doi.org/10.1057/9781137-446671_1

[11] Hamann, J., Ringel, L. (2023). The discursive resilience of university rankings. Higher Education, 86, 845–863. https://doi.org/10.1007/s10734-022-00990.

[12] Chai, J., Zhou, J. (2025). Skyline SIR method for university ranking: Case studies based on QS, THE, and ARWU rankings. *In* 2025 17th International Conference on Advanced Computational Intelligence (ICACI) (p. 326–333). *IEEE*. https://doi.org/10.1109/ICACI65340.2025.11096158.

[13] Jeremic, V., Jovanovic-Milenkovic, M. (2014). Evaluation of Asian university rankings: Position and perspective of leading Indian higher education institutions. *Current Science,* 106(12), 1647–1653.

[14] Buela-Casal, G., Gutiérrez-Martínez, O., Bermúdez-Sánchez, M. P., Vadillo-Muñoz, O. (2007). Comparative study of international academic rankings of universities. Scientometrics, 71(3), 349–365. https://doi.org/10.1007/s11192-007-1653-8.

[15] Van Raan, A. F. J. (2005). Fatal attraction: Conceptual and methodological problems in the ranking of universities by bibliometric methods. Scientometrics, 62(1), 133–143. https://doi.org/10.1007/s11192-005-0008-6.

[16] Billaut, J. C., Bouyssou, D., Vincke, P. (2010). Should you believe in the Shanghai ranking An MCDM view. Scientometrics, 84(1), 237–263. https://doi.org/10.1007/s11192-010-0205.

[17] Huang, M. H. (2012). Opening the black box of QS World University Rankings. Research Evaluation, 21(1), 71–78. https://doi.org/10.1093/reseval/rvr003.

[18] Docampo, D., Cram, L. (2014). On the internal dynamics of the Shanghai ranking. Scientometrics, 98(2), 1347–1366. https://doi.org/10.1007/s11192-013-1146-7.

[19] Marginson, S. (2014). University rankings and social science. *European Journal of Education,* 49(1), 45–59. https://doi.org/10.1111/ejed.12061.

[20] Moed, H. F. (2017). A critical comparative analysis of five world university rankings. Scientometrics, 110(2), 967–990. https://doi.org/10.1007/s11192-016-2212.

[21] Gupta, S., Kanaujia, A., Bhattacharya, S., Singh, V. (2023, April). International university rankings and changing university functions: Underlining indicators to capture societal and entrepreneurial contributions of universities. *In* Proceedings of the 27th International Conference on Science, Technology and Innovation Indicators (Vol. 1 (1).

[22] Ferro, G., Dip, J. A. (2026). The three global rankings of universities: The why, the how, and the what are they informing Scientometrics. Advance online publication. https://doi.org/10.1007/s11192-026-05663-5

[23] Mammola, S., Piano, S., Doretto, A., Caprio, E., Chamberlain, D. (2022). Measuring the influence of non-scientific features on citations. Scientometrics, 127, 4123–4137. https://doi.org/10.1007/s11192-022-04421-7

[24] Moskovkin, V. M., Serkina, O. V. (2016a). Is sustainable development of scientific systems possible in the neo-liberal agenda Ethics in Science and Environmental Politics, 16, 1–9. https://doi.org/10.3354/esep00167.

[25] Moskovkin, V. M., Serkina, O. V. (2016b). What is the cost of bibliometric games to taxpayers Webology, 13(2), Article 148.

[26] Zheng, Y., Cao, Y. (2019). Study on comparison of Chinese and foreign first-class universities based on grey correlation analysis. *In* Proceedings of the First International Conference on Science Technology Metrics (STMet 2019) (p. 51–67). *Bangkok, Thailand.*