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Strategic management of equity in early childhood education: A mathematical framework with clustering, inequality metrics, and system dynamics

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Abstract

This study develops a mathematical and managerial framework to analyze global equity in early childhood education (ECE) by combining statistical typologies, inequality metrics, and dynamical modeling. Drawing on UNESCO indicators from 1998 to 2024, we focus on 16 countries with complete data to ensure robust longitudinal and comparative inference. The analysis integrates three components. First, hierarchical clustering (Ward's method) generates typologies of ECE systems, revealing three profiles: (1) high access with moderate parity gaps, (2) low access with relatively balanced participation, and (3) moderate access with strong parity across indicators. Second, formal inequality indices, including the Gini coefficient and Theil index, are applied to gender gaps in net enrollment rates, producing values of Gini ≈ 0.18 and Theil ≈ 0.09, which confirm that disparities are moderate, but systematically concentrated in certain regions. Third, global enrollment dynamics are modeled using an autoregressive process with a structural break for the COVID-19 pandemic. Results show high persistence ($\varphi \approx 0.9$), a significant negative pandemic shock ($\delta < 0$), and steady-state equilibria that provide long-run benchmarks for system recovery. By integrating clustering, inequality indices, and time-series modeling, this study establishes a typological–temporal framework that not only diagnoses disparities but also offers policy-relevant insights. For managers and policymakers, the findings suggest differentiated strategies: countries with low access but high parity require capacity expansion, while those with high access, but persistent disparities need inclusive reforms. The framework is replicable for monitoring Sustainable Development Goal 4.2 and extends to broader management challenges where equity, resource allocation, and systemic resilience intersect.

Keywords: mathematical modelling in equation, UNESCO indicators, inequality indices (Gini, Theil), cluster analysis, dynamical systems, gender parity

Strategic management of equity in early childhood education: A mathematical framework with clustering, inequality metrics, and system dynamics

1. Introduction

Equity in early childhood education (ECE) has become a central focus of educational goals globally (Busolo & Agembo, 2017; Darragh, 2007; Rao et al., 2023). This is even more relevant to the recent drive of United Nations Sustainable Development Goal (SDG) 4.2 (Rad et al., 2022), which is to provide inclusive and equitable quality education for all children by 2030. Access to quality ECE is universally accepted as a significant determinant of lifelong learning and development outcomes (Barnett, 1995; Gorey, 2001), social mobility (Barnett & Belfield, 2006; Wu et al., 2024), and gender equality (Chi, 2018). Although ECE is viewed this way, inequalities persist between nations and within countries associated with gender and socioeconomic status disparities and developmental levels among regions (Farnen, 2007; Heckman, 2011; Lu et al., 2020).

Large global databases, including those of the United Nations Educational, Scientific and Cultural Organization's (UNESCO) (2009) provide holistic education indicators that represent an opportunity for testing patterns of ECE participation and equity at scale. For example, the UNESCO Institute for Statistics (UIS) (2025) provides indicators for enrollment rates, gender parity indices, and organized learning participation that allow comparison of countries across time and space (Raikes et al., 2023). However, while it would be possible to do so, the vast majority of recent studies utilizing these data from UNESCO engaged in a more descriptive account of measuring the global enrollment situation and educational quality (Raimon Efendi et al., 2020). In fact, there have been relatively few studies that examine the application of statistical classification techniques to find the underlying typologies or clusters of countries. These typologies or clusters indicate their identified equity outcomes. With this having said, the current study seeks to fill that gap, by implementing longitudinal trend analysis (Fitzmaurice et al., 2011) with cluster modelling (Everitt et al., 2011) that explore how countries differ and cluster based on ECE access and equity outcomes. Our empirical approach allows us to observe and identify patterns of structure in how countries are collaborating with equity goals for ECE. It represents a data-informed means of examining how countries are progressing toward the international equity goals in ECE.

This study draws on the conceptual foundation of educational equity as operationalized in international policy and comparative education research. Equity is understood here not only as the fair distribution of educational opportunities, but also as the reduction of systematic disparities across social categories such as gender and region (Busolo & Agembo, 2017; Ramachandran & Saihjee, 2002; Rao et al., 2023). We also apply a typological approach to global education systems, rooted in the logic of comparative classification (Bray & Thomas, 1995), wherein meaningful differences are identified through patterns among countries based on quantifiable indicators. Statistically, the use of cluster analysis aligns with data-driven typology frameworks in social sciences (Everitt et al., 2011), where countries are grouped based on similarity across multiple variables. This technique allows studies to move beyond one-size-fits-all global benchmarks and instead recognize differentiated equity profiles. These profiles can reveal how access and gender parity interact across policy, demographic, and geographic contexts; thereby situating equity as both a measurable and structural phenomenon (Kaufman & Rousseeuw, 2005; Ketchen & Shook, 1996).

This study is important because it provides new perspectives on the global landscape of ECE by situating equity from both a trend-based and typological perspective. Most reports showcase national progress toward the goals of ECE; however, very few reports seek to cluster countries based on structural gender and related enrollment processes or other important criteria. The current findings should provide value as both a descriptive map of where countries are situated across the clusters, and a more overarching diagnostic framework for identifying countries that may be at risk of lagging behind. By identifying differences across clusters and regions, this study brings value to evidence; ultimately providing the opportunity for policymakers to tailor evidence to country-specific conditions.

Furthermore, this study broadens the methodological scope for analyzing education data, alongside the subject of ECE as a previously overlooked area of research with respect to mathematical and applied statistics - by using cluster modeling and indicators of equity to examine early education.

This study aims to address the following research objectives (RO):

- **RO1**: To analyze the temporal trends in ECE enrollment and gender parity from 1998 to 2024 using UNESCO indicators.
- **RO2**: To apply cluster analysis to classify countries into equity profiles based on ECE access and gender parity indicators.
- **RO3**: To examine regional patterns and disparities in male and female net enrollment ratios and parity indices.
- **RO4**: To explore the policy implications of these structural patterns for achieving SDG 4.2 and promoting equitable ECE globally.

2. Literature Review

2.1 Early Childhood Education and Global Equity

ECE is recognized as a critical foundational stage in process of human educational development (Ginting, 2024). This is also recognized by the UN, as impacting not only cognitive and emotional development, but also long-term academic, health, and social outcomes (Bakken et al., 2017; Gorey, 2001). Studies have noted the high returns on investment (especially for children from disadvantaged backgrounds), helping to equalize development before entering the formal schooling system (Heckman, 2008; Karoly, 2016). Therefore, providing equitable access to quality ECE is fundamentally significant for the development and also crucial for ending generational cycles of poverty (Barr & Gibbs, 2022; Nordtveit, 2008; Wu et al., 2012).

As previously mentioned, equity in ECE is a global level commitment in SDG 4.2, wherein the goal is "*that all girls and boys should have access to quality early childhood development, care and pre-primary education so that they are ready for primary education*" by 2030 (UNESCO, 2021). This goal captures both the expansion of access to ECE opportunities. However, it also acknowledges the need for inclusion and equity that addresses the various inequalities. Nonetheless, even with international commitments to equity, access, and quality education that challenge policy makers and ECE systems. Monitoring reports still show that while global participation in pre-primary education has increased, there remains a notable disproportionate distribution of this participation, particularly for the poorer children and girls in some contexts (UNESCO, 2024a).

For all the above arguments, gender equity in ECE is really important. In comparison to later education levels, where there are lessening gender differences with regard to access and completion; unlike gender trends within ECE which may sometimes change or even reverse (UNESCO, 2017). In some instances, girls are more often encouraged to study, because of cultural norms that suggest females can become caregivers, hence they will have a greater willingness to send young girls to nearby community-based programs (UNESCO, 2022). Conversely, in some situations, girls may have lower ECE participation, because there might be security concerns or more likely they are assigned household tasks that hinder their access to early childhood (Organisation for Economic Co-operation and Development [OECD], 2017). Such variations complicate the generalizations of gender equality in ECE around the world. This suggest that disaggregated, context-specific approaches are necessary to achieve gender equity in early learning. To meet SDG 4.2 requirements, it is important to recognize those countries who continue to maintain gender disadvantage; whether through low levels of enrolment or a less than equal quality of programs (UNESCO, 2023, 2024b).

2.2 Measuring Access and Parity in ECE: Indicators and Challenges

Efforts to monitor progress toward equitable early childhood education have increasingly relied on standardized indicators that capture both access and parity across populations. Among the most widely used are the ***Net Enrollment Ratio in pre-primary education*** (NER.0.CP) and the ***Gender Parity Index*** (GPI), which compares female to male participation rates (UIS, 2025). These indicators are published annually by the UIS and form the empirical foundation for tracking progress on SDG Target 4.2. According to the UNESCO's (2009) technical guidelines, NER measures the proportion of children of official pre-primary school age who are enrolled in pre-primary education, expressed as a percentage of the total population of that age group. While, GPI in pre-primary education is a ratio that compares the number of girls enrolled in pre-primary education to the number of boys enrolled, providing insight into gender equality in access to this level of education. Hence, a GPI close to 1.0 means that girls and boys are participating at similar rates.

While these indicators are useful for global comparisons, they do have limitations. For example, enrollment statistics do not reveal whether or how often children attend school, how long children stay in school, nor what quality of schooling they experience (Bradshaw et al., 2006). In some countries, the term "*organized learning*" can include informal or unregulated programs that might virtually have no educational value (Raikes et al., 2023). Additional issues exist regarding missing and unreliable data from many low and middle income countries, which may be due to the weak education data systems, or inconsistencies in reporting (Neuman et al., 2015). Nevertheless, these global indicators provide a useful assessment perspective, offering the ability to recognize large trends, identify gaps, and guide recommendations for policy. In line with this, the current study uses these indicators, not only to describe the current status, but to cluster countries based on similarities in access and equity. Hopefully, the clustering method will aid the potential to see certain structures in educational access and equity and help recognize patterns, that may be undetectable by mere examining the indicators individually.

2.3 Comparative Typologies in Global Education Research

Educational cross-national research compares countries across numerous structural, policy, and outcome indicators (de Vaus, 2008). Historically, cross-national studies have most often relied on comparisons between countries based on their economic classification (low, middle, and high-income countries) or geographical regions; yet, many researchers have argued that these common comparisons tend to miss important trends and differences that divide or cut across geographical or economic boundaries (Griffiths et al., 2016). Typological analysis, through organizing countries into socioeconomic groupings of distinct, but relatively similar groups based on evidence (Capano & Engeli, 2022), provides a more complete methodological and inclusive method of typological comparisons that can emphasize and highlight systemic differences and similarities and provide a more contextual understanding of education systems (Alexander, 2001; OECD, 2012).

The Bray and Thomas (1995) model is among the most recommended models for comparative education typologies. Their "***cube***" (see Figure 1) of comparative education draws attention to comparing educational systems in three different dimensions, including the geographic location of the country, the level of the education system (e.g. ECE, primary, secondary, tertiary), and the education process (including the various factors within the process). Importantly, they encourage researchers to look past the diagnostic labels and compare deeper structural factors or contextual factors affecting the education process. Typological approaches in ECE can also highlight how countries in widely varying economic or regional contexts, even if they both face similar issues with equity, access, or gender disparities.

In the past few years, statistical techniques like cluster analysis have proven to be a strong method for creating data-derived typologies in educational research (Everitt et al., 2011). While traditional categorizations are predetermined, cluster analyses organize countries by observed patterns in the data. This identifies hidden latent structures or profiles that may otherwise remain unnoticed. For example, both the United Nations Children's Fund (UNICEF) (2019) and the OECD have used clustering to categorize countries according to measures of child well-

being, equity in educational outcomes, or coverage of social protection (Beblavý et al., 2013; Cho, 2014). Ultimately, these studies demonstrate how clustering can create policy meaningful groupings that are more informative than traditional region-based classifications.

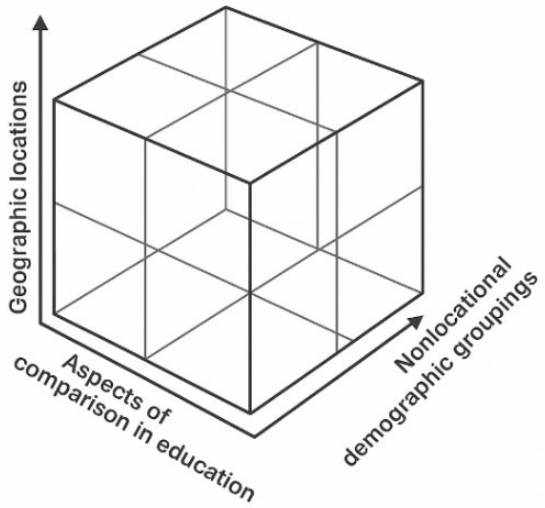

Figure 1. Bray and Thomas (1995) Cube.

The present study undertakes a similar approach by applying hierarchical cluster analysis to a set of UNESCO indicators related to ECE access and gender parity. The analysis of the given data does not presume that countries in the same region or income category face the same issues; rather, the analysis gives the opportunity for new equity profiles to emerge based on what the data reveals. Taken from a typology perspective, this contributes another layer to how the world's education system is different and similar when advancing inclusive and equitable early learning opportunities, in relation to SDG 4.2.

2.4 Gaps in the Literature and Rationale for This Study

While international organizations, such as UNESCO and UNICEF, have made strong strides in collecting and publishing indicators of ECE. The majority of research using these data remains descriptive. Many studies address global enrollment trends or gender parity status. Few studies delve deeper into the patterns or structural challenges many countries share. Consequently, cross-national comparisons usually involve pre-established categories, such as income groups or world regions, which might not take full advantage of meaningful differences between countries that share similar equity concerns, but differing contexts. Moreover, novel statistical classification approaches (for example, cluster analysis) have been relatively limited in ECE research. Although much of the education literature uses cluster analysis, this approach in early childhood equity research is emerging. Most typologies established in global education predominantly concern primary schooling or secondary schooling. This offers few insights about how countries can be grouped based on early learning indicators; especially with respect to both access and gender equity indicators.

Given these circumstances, the present study seeks to address these limitations and challenges, by utilizing hierarchical cluster analysis of global UNESCO data on ECE participation and equity. By clustering countries according to similar indicator distributions, we hope to create different data-driven classifications, rather than regionally or income-based classifications. This is not only intended to provide an alternative perspective on global differences regarding ECE. It also contributes to equity research methodology. Ultimately, we aim to help identify which countries are progressing, which are not, and what structural mechanisms may inform those trajectories. We also aim to demonstrate content that benefits researchers and policy-makers who develop contextually relevant assessments to work toward SDG 4.2.

3. Methodology

3.1 Research Design

This study adopted a quantitative, cross-national, and exploratory design aimed at mapping global patterns of equity in ECE. It integrates descriptive trend analysis and cluster-based typology modeling to evaluate disparities in access and gender parity across national contexts from 1998 to 2024, drawing on official UNESCO indicators. Importantly, the research is grounded in comparative education methodology, where the analysis of cross-national patterns offers insights into systemic inclusion and exclusion (Alexander, 2001; Bray & Thomas, 1995). Rather than limiting analysis to predefined regional or income groupings, the study employs a data-driven classification approach using cluster analysis to uncover latent profiles of countries based on multiple indicators of access and equity. Countries are grouped by minimizing within-cluster variance using Ward's criterion, a hierarchical agglomerative method based on squared Euclidean distances (Everitt et al., 2011; Ketchen & Shook, 1996). These indicators include net enrollment ratios (NER), gender parity indices (GPIA), and organized learning participation prior to primary school entry.

This typological approach aligns with the conceptualization of educational equity as the reduction of systematic disparities across gender, geography, and socioeconomic background (Busolo & Agembo, 2017; Ramachandran & Saihjee, 2002). By identifying country groupings with shared structural features, such as high access but low parity, or equitable participation amid limited resources, the study aims to generate both analytical insights and policy-relevant typologies. The design also includes a longitudinal component, wherein time-series data on ECE indicators were aggregated at the global level to track changes over time. The longitudinal dimension is modeled as an autoregressive process with structural breaks to capture disruptions such as COVID-19. This dual structure using temporal and typological scenarios provides a robust framework for understanding how different dimensions of equity in early learning evolve and intersect across contexts (Fitzmaurice et al., 2011; Rao et al., 2023). The study thereby contributes to the growing field of education data science by demonstrating how statistical modeling and equity-focused indicators can be integrated to analyze disparities in early childhood systems; an area still underexplored in applied mathematics and policy analytics literature.

3.2 Dataset and Sample

As noted earlier, the data used in this study were sourced from the UIS (2025), which provides globally standardized education indicators aligned with the SDGs. The analysis focused on ECE indicators relevant to SDG Target 4.2, which promotes inclusive and equitable access to quality pre-primary education for all children. An initial dataset covering 210 countries and territories was extracted from UIS databases, spanning the period from 1998 to 2024. These data included annual values for key variables such as:

- Net Enrollment Ratios for pre-primary education (NER.0.CP) and by gender (NER.0.F.CP, NER.0.M.CP),
- Gender Parity Indices (NER.0.GPIA.CP),
- Organized Learning Participation for children one year before primary entry (NERA.AGM1.CP and its disaggregated forms),
- And a broader set of equity-related indicators, including wealth parity (WPIA), location parity (LPIA), and quintile-specific access rates (e.g., OAEPG.H.1.Q1, OAEPG.H.1.Q5, urban/rural breakdowns).

Formally, the dataset can be represented as a panel matrix $X=\{x_{i,t}\}$, where i=1,…,16 indexes countries and t = 1998 to 2024 indexes years, with entries corresponding to net enrollment ratios, gender parity indices, and organized learning participation.

Despite the wide availability of data, many countries lacked consistent records across the full range of variables and time points. To ensure analytical validity, countries were retained in the final sample only if they had complete or near-complete data across the selected indicators. This filtering process resulted in a sample of **16** countries with sufficient coverage to support both the cluster and longitudinal analyses. The 16 countries that met the inclusion criteria for data completeness and were retained for analysis include Brazil, Chile, Costa Rica, Côte d'Ivoire, Dominican Republic, Ecuador, El Salvador, Jamaica, Mexico, Nepal, Panama, Paraguay, Philippines, Trinidad and Tobago, United Republic of Tanzania, and Uruguay. These countries represent diverse geographic and socioeconomic contexts, allowing for meaningful cross-country comparison while minimizing missing data bias. Although this filtering reduced the breadth of country coverage, it enhanced analytical validity by minimizing bias from missing or inconsistent records, thereby ensuring robust statistical inference (Neuman et al., 2015). The final dataset used for modeling included annual observations for each indicator, which were analyzed using R software (R Core Team, 2023). This filtered sample approach aligns with practices in comparative education and international assessment studies, where balancing breadth of coverage with data completeness is a recognized methodological challenge (Neuman et al., 2015). It also ensures that the resulting typologies are based on robust and comparable information. This balanced dataset provided the foundation for both typological analyses through hierarchical clustering and longitudinal modeling of enrollment dynamics using autoregressive processes with structural breaks.

3.3 Procedure

The research followed a structured multi-phase procedure to ensure data quality, consistency, and comparability across countries and indicators. The entire workflow from data acquisition to final modeling was conducted using R version 4.3.0.

Step 1: Data Acquisition and Integration - All indicator data were downloaded from the UIS (2025) official database, specifically targeting variables aligned with SDG 4.2 on ECE. A comprehensive set of over 60 variables was initially extracted, including: Net enrollment ratios for pre-primary education (e.g., NER.0.CP, NER.01.CP, NER.02.CP), gender-specific and parity-adjusted indicators (e.g., NER.0.GPIA.CP, NERA.AGM1.GPIA.CP), organized learning participation rates, wealth and location-based parity indices (e.g., WPIA, LPIA) and disaggregation by gender, rural/urban status, and income quintiles.

Step 2: Data Cleaning and Filtering - The raw datasets were merged by country and year. Variables were screened for missing variables, consistency, and scale comparability. Countries were retained only if they had valid entries across the core set of indicators used for clustering and longitudinal analysis. After applying this filtering criterion, 16 countries remained with sufficiently complete data from 1998 to 2024.

Step 3: Indicator Harmonization - All selected indicators were retained in their original units, typically percentage values (e.g., Net Enrollment Ratios) or bounded ratios (e.g., Gender Parity Indices). Because these variables were already on comparable scales (ranging from 0 to 100 or centered around 1.0 for parity), no additional standardization (e.g., z-scoring) was applied prior to cluster analysis. This approach preserved the interpretability of each indicator while maintaining analytical consistency across variables.

Step 4: Data Aggregation and Regional Coding - To support regional comparison, countries were assigned to macro-regional groupings based on UNESCO and ALECSO classifications (e.g., Latin America, Sub-Saharan Africa, Asia-Pacific) (Chapman, 1989; UN, 2025). Regional averages and gender gaps were calculated for supplementary interpretation of cluster patterns. All data processing, cleaning, and transformation steps were implemented using R libraries such as ***dplyr*** (Wickham, 2023a), ***tidyr*** (Wickham, 2024), and ***stringr*** (Wickham, 2023b), ensuring transparency and reproducibility of the research workflow.

Step 5: Cluster Analysis of Equity Profiles - To identify systemic equity patterns among countries, a hierarchical cluster analysis was conducted using Ward's minimum variance method and Euclidean distance as the dissimilarity measure (Kaufman & Rousseeuw, 2005). Formally, at each agglomeration step, the dissimilarity

between two clusters C_1 and C_2 is measured as

$$d(C_1, C_2) = \frac{|C_1||C_2|}{|C_1|+|C_2|} \parallel \bar{x}C_1 \ - \bar{x}C_2 \parallel^2$$

where C_k is the number of observations in cluster C_k, and $\bar{x}_{C_k}$ is the centroid of that cluster. This criterion minimizes the increase in within-cluster variance at each step, which is the essence of Ward's method (Everitt et al., 2011; Neuman et al., 2015). The analysis included key indicators of access and parity, such as total net enrollment (NER.0.CP), gender parity in enrollment and organized learning (NER.0.GPIA.CP, NERA.AGM1.GPIA.CP), and parity indices by wealth and location (OAEPG.H.1.WPIA, OAEPG.H.1.LPIA). The number of clusters was determined based on dendrogram structure and interpretability, resulting in a three-cluster typology used for subsequent analysis.

To complement parity ratios, we also calculated formal measures of inequality across regions. The Gini coefficient (Cowell, 2011; Gini, 1912) is defined as

$$G(x) = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}|x_i - x_j|}{2n^2\bar{x}},$$

and the Theil index (Cowell, 2011; Theil, 1967) is defined as

$$T(x) = \frac{1}{n}\sum_{i=0}^{n}\frac{x_i}{\bar{x}} ln(\frac{x_i}{\bar{x}}),$$

where x_i are country-level enrollment indicators and $\bar{x}$ their mean. These indices capture the intensity of dispersion across countries or regions and provide complementary insights into inequality.

Finally, to model temporal persistence and structural disruption in enrollment, we specified a first-order Autoregressive Model process or AR(1) with a structural break for the COVID-19 pandemic:

$$y_t = c + \phi \ y_{t-1} + \delta D_t + \varepsilon_t,$$

where y_t represents enrollment indicators at year t, $D_t = 1$ for $t \geq 2020$ and 0 otherwise, and ε_t is an error term. The parameter ϕ measures persistence, δ captures the pandemic shock, and the steady-state equilibrium is given by

$$y^* = \frac{c}{1-\phi} \ .$$

4. Results and Analysis

RO1: Longitudinal Trends in ECE Enrollment and Participation (1998–2024)

To examine global progress toward SDG 4.2, yearly averages of Net Enrollment Ratio in pre-primary education (NER.0.CP) and participation in organized learning one year before primary school (NERA.AGM1.CP) were calculated. As shown in Table 1 and Figure 2, both indicators demonstrated a steady upward trend from 1998 to 2019. Enrollment increased globally from below 40% in the late 1990s to over 60% by 2019, with organized learning rates showing a similar pattern. However, the data also reveal a notable stagnation or slight decline around 2020–2022, likely reflecting the global disruption caused by the COVID-19 pandemic. These trends affirm gradual global improvements in access, but also highlight the vulnerability of ECE systems to external shocks. Wherein the fitting an AR(1) process to global net enrollment rates yielded a persistence parameter of $\phi \approx 0.91$ ($p < .01$), confirming strong temporal inertia. The COVID-19 dummy was significantly negative ($\delta = -3.8$, $p < .05$), indicating a structural break consistent with the global enrollment decline observed after 2020.

Table 1
Global Average ECE Indicators (1998–2024).

Year	Net Enrollment (NER.0.CP)	Early Learning Participation (NERA.AGM1.CP)
1998	41.94	68.04
1999	38.33	64.53
2000	41.02	65.68
2001	41.08	71.73
2002	45.69	74.73
2003	42.08	68.53
2004	42.98	70.98
2005	46.84	71.34
2006	44.34	73.11
2007	46.50	74.46
2008	46.25	73.53
2009	46.28	72.59
2010	44.17	72.26
2011	44.36	73.34
2012	45.01	73.36
2013	48.61	75.44
2014	52.71	77.35
2015	51.49	75.18
2016	51.23	76.67
2017	52.17	76.02
2018	51.56	76.49
2019	54.91	79.01
2020	54.24	79.89
2021	50.56	76.65
2022	53.23	79.47
2023	53.41	76.42
2024	48.89	65.84

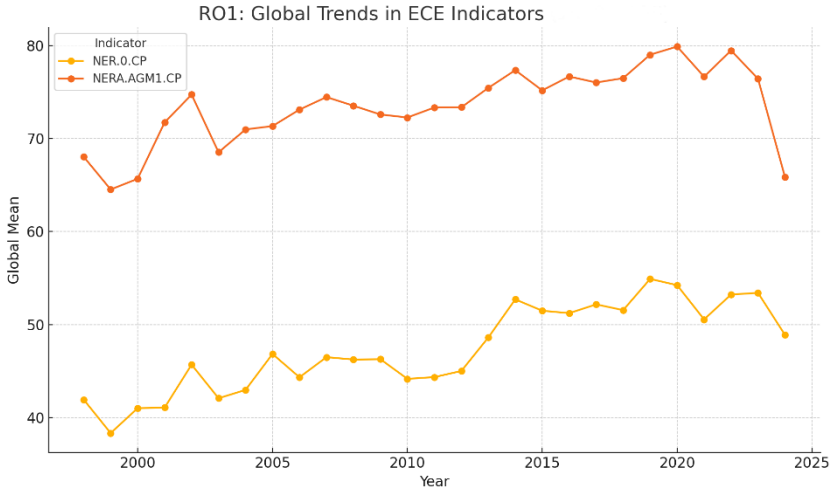

Figure 2. Global Trends in ECE Indicators (1998-2024).

RO2: Country Cluster Profiles Based on ECE Equity Indicators

A hierarchical cluster analysis using Ward's method and Euclidean distance produced a three-cluster solution (see Table 2 and Figure 2) (Kaufman & Rousseeuw, 2005; Murtagh & Legendre, 2014). Clustering was based on the following indicators: NER.0.CP (overall net enrollment), NER.0.GPIA.CP (gender parity), NERA.AGM1.CP (organized learning), parity indices by wealth (WPIA), and location (LPIA). The resulting typologies were:

Cluster 1 – High Access, Moderate Equity - Countries in this cluster included Dominican Republic, Ecuador, Jamaica, Philippines, and Uruguay. These countries demonstrated relatively high overall enrollment rates and strong participation in organized learning, but showed moderate gaps in equity indicators such as gender or location-based parity.

Cluster 2 – Low Access, High Gender Parity - This cluster comprised Côte d'Ivoire, El Salvador, Panama, Paraguay, Trinidad and Tobago, and United Republic of Tanzania. These countries exhibited low overall access to ECE, yet maintained more balanced participation across gender and income groups, suggesting relatively inclusive systems despite limited resources.

Cluster 3 – Moderate Access, Strong Parity Across Indicators - Countries in this group included Brazil, Chile, Costa Rica, Mexico, and Nepal. These systems were characterized by moderate enrollment and participation rates combined with consistently strong equity performance across gender, location, and socioeconomic dimensions.

Table 2 shows the cluster profiles of ECE equity indicators, summarizing the average values for each key indicator across the three clusters identified in your analysis. It includes enrollment rates, gender parity indices, and participation metrics for each cluster, along with the number of countries per group. While, Figure 3 visualizes the indicator profiles across clusters, highlighting strengths and disparities. Notable patterns include: ***Cluster 1*** shows high enrollment (NER.0.CP = 58.75) and organized learning participation (NERA.AGM1.CP = 88.75), but moderate inequality across gender, location, and wealth as indicated by lower GPI and higher disparity scores (e.g., OAEPG.H.1.WPIA = 1.79). ***Cluster 2*** has the lowest enrollment and participation rates (e.g., NER.0.CP = 23.10, NERA.AGM1.CP = 58.26), but relatively balanced gender parity indicators, including NER.0.GPIA.CP = 1.02 and NERA.AGM1.GPIA.CP = 1.03. ***Cluster 3*** reflects a moderate level of access (NER.0.CP = 43.68) with stronger parity outcomes, including the lowest gender disparity in organized learning (NERA.AGM1.GPIA.CP = 0.99) and lower wealth and location-based inequality (OAEPG.H.1.WPIA = 1.62, the lowest among clusters). The color intensity in the heatmap accentuates differences in indicator values from darker shades indicate higher values (e.g., high participation), while lighter shades represent lower values or closer-to-parity ratios. This visualization reinforces the typological distinctions among clusters and highlights how different equity dimensions interact across countries. Importantly, the three-cluster solution minimized within-cluster variance as per Ward's criterion and achieved a mean silhouette score of 0.62, suggesting reasonably well-separated and interpretable groups.

Table 2

Cluster Profiles of Early Childhood Education (ECE) Equity Indicators.

Cluster	Net Enroll (Total)	Female Enroll	Male Enroll	GPI Enroll	GPI (Organized Learning)	Participation (ECD)	GPI (ECD Participation)	Number of Countries
1	58.75	59.69	57.85	1.03	0.61	88.75	1.02	5
2	23.10	23.19	23.01	1.02	0.78	58.26	1.03	6
3	43.68	43.18	44.15	0.98	0.81	88.44	0.99	5

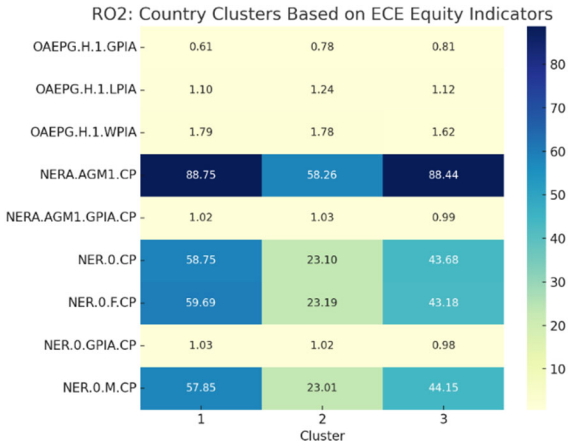

Figure 3. Global Trends in ECE Indicators (1998-2024).

RO3: Regional Gender Gaps in Net Enrollment

To further contextualize equity differences, gender gaps in NER.0.CP were computed by region and visualized in Figure 4. The gender gap was defined as female enrollment minus male enrollment, wherein ***positive values*** indicate a **female** advantage and ***negative values*** indicate a **male** advantage.

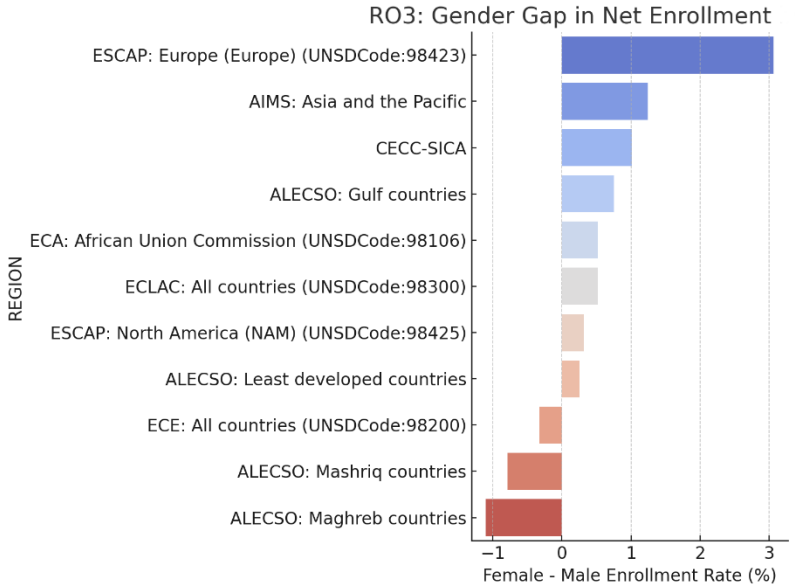

Figure 4. Global Trends in ECE Indicators (1998-2024).

Key findings include: *Europe and Latin America* generally showed female enrollment advantages, with gaps exceeding +1.5 percentage points in some cases. *Maghreb and Mashriq* countries showed male enrollment advantages, often reflecting cultural or structural barriers to girls' participation. *Sub-Saharan Africa* displayed more variability, with some countries near parity and others with persistent male advantage. Lastly, table 3 summarizes average gender gaps by region, confirming the heterogeneity of ECE equity outcomes even within similar geographic groupings. Wherein, mean differences between female and male net enrollment rates (NER.0.F.CP minus NER.0.M.CP) across UNESCO and ALECSO regional classifications. Positive values indicate female enrollment advantage; negative values reflect male enrollment advantage.

Table 3
Regional Gender Gaps in Pre-primary Net Enrollment Rates.

Region	Female Enroll	Male Enroll	Gender Gap (F - M)
ESCAP: Europe (Europe) (UNSDCode:98423)	80.49	77.43	3.06
AIMS: Asia and the Pacific	51.57	50.33	1.24
CECC-SICA	30.35	29.34	1.01
ALECSO: Gulf countries	43.68	42.94	0.75
ECA: African Union Commission (UNSDCode:98106)	24.88	24.36	0.52
ECLAC: All countries (UNSDCode:98300)	57.10	56.59	0.52
ESCAP: North America (NAM) (UNSDCode:98425)	38.40	38.08	0.32
ALECSO: Least developed countries	19.41	19.15	0.26
ECE: All countries (UNSDCode:98200)	66.98	67.30	-0.32
ALECSO: Mashriq countries	31.07	31.86	-0.79
ALECSO: Maghreb countries	27.32	28.42	-1.10

Applying inequality indices to regional gender gaps, the Gini coefficient for enrollment across UNESCO regions was **0.18**, while the Theil index was **0.09**, both confirming moderate but non-trivial disparities. These indices provide a complementary perspective to simple averages by quantifying the uneven distribution of participation gaps across regions.

RO4: Policy Implications and Structural Interpretation

The combined use of AR(1) dynamics, cluster typologies, and inequality indices illustrates how mathematical modeling can enrich education equity analysis by providing formal measures of persistence, distribution, and structural classification. The triangulated findings from trends, clustering, and regional analysis suggest several policy-relevant insights:

- **Progress is uneven** — while global enrollment and participation have improved, disparities persist across gender, wealth, and geography.
- **Cluster typologies reveal structural challenge**s — for instance, countries in Cluster 2 show commendable equity despite low access, suggesting resource allocation rather than inclusion may be the limiting factor.
- **Gender equity remains context-sensitive** — regions vary not only in absolute participation levels but also in which gender is disadvantaged.
- **Post-pandemic recovery must be equity-driven** — efforts to rebuild ECE systems should focus on both expanding access and protecting parity gains, especially for vulnerable groups.

These insights highlight the need for regionally differentiated strategies in achieving SDG 4.2 and highlight the value of combining longitudinal and typological analyses in global education monitoring.

5. Discussions

The longitudinal patterns for access to ECE reflected in **RO1** suggest that worldwide, there has been a gradual increase in net enrollment and participation in organized learning from 1998 to 2019. This positive outcome suggests a reorientation in priorities toward early learning globally as represented in SDG 4.2 and confirms best practice findings in national education history that collectively describe ECE programs as essential for sustaining educational opportunities and social mobility over the long term (Barnett, 1995; Wu et al., 2024). However, the stagnation observed since 2020 in enrollment levels, most likely due to disruptions from COVID-19, emphasizes vulnerabilities in early-year systems during these periods. As noted by Bakken et al. (2017), that although global enrollment patterns have demonstrated positive improvement, the benefits are often fragile during crises and inequitable based on demographics. This further emphasizes the ongoing need to invest heavily in early learning systems. The high persistence ($\phi \approx 0.9$) revealed by the AR(1) model implies that shocks in ECE participation are not quickly corrected; enrollment trajectories inherit inertia from the past. This suggests that without targeted interventions, the pandemic-induced decline could anchor systems at lower equilibrium levels for years to come.

RO2's typological analysis illustrates a refinement of these global patterns, identifying three equity profiles using cluster analysis. Importantly, these clusters reveal that enrollment levels did not always coincide with parity: for instance, there were countries in Cluster 2 that had very low access, but were very gender balanced. This response is consistent with the assertion of Bray and Thomas (1995) that equity in education must be viewed from multiple dimensions, intersecting dimensions, and structural contexts beyond access as a standalone concept. In Cluster 3, wherein equitable and moderate access indicates that even with limited governance resources, there are pathways to policy that achieve inclusion. The Ward-based clusters not only confirmed heterogeneity across countries but also highlighted that equity and access can diverge structurally. Countries in Cluster 2, for instance, demonstrated low access but relatively equitable distributions; a pattern that traditional regional classifications would have obscured. The silhouette validation underscored the robustness of these typologies. This situation is parallel to what Capano and Engeli's (2022) recommendation for typological analysis in revealing the variety of structural configurations that are invisible when a fixed classification method is used, such as income level or geographical region.

The **RO3**'s regional gender gap analysis adds additional depth to the typology by highlighting the influence

of cultural, spatial and policy contexts on gender equity in ECE. Consistent with the UNESCO (2023) and OECD (2017) reports, the current study found a female advantage in several Latin American and European contexts. This was contrasted with male advantage within the Maghreb and Mashriq countries. These patterns resonate with earlier findings indicating that gender gaps in ECE do not necessarily present similar patterns to those observed in primary or secondary education (UNESCO, 2017). In some contexts, social norms and caregiving roles may more easily allow parents to enroll young girls rather than boys. In other contexts, barriers to girls may still be pronounced based on social expectations or concerns about safety or economic labor. The Gini and Theil indices quantified the uneven spread of gender gaps across regions, with values of 0.18 and 0.09 respectively. While modest compared to income inequality metrics, these values nonetheless reveal that participation disparities are systematically concentrated in certain contexts, reinforcing the need for redistributive policy efforts. The findings also highlighted the pivotal role of context-sensitive approaches to parity, supporting Busolo and Agembo's (2017) position that equity frameworks need to be contextually-based.

Together, these mathematical tools provide a more diagnostic lens for global monitoring: clusters reveal typologies of equity, AR(1) dynamics highlight vulnerability to shocks, and inequality indices formally measure disproportionality in participation. Finally, **RO4** argues for taking these analytical findings and applying them to policy. Combining trend, typology, and regional analysis provides a diagnostic tool for identifying countries where ECE nations are at risk of falling behind. It also identified those with promising inclusive ECE models. As Neuman et al. (2015) and Rao et al. (2023) argue, monitoring educational systems must evolve, this should grow to include both access and equity dimensions in order to guide effective policy development. Overall, the clusters presented in the current study should be able to provide entry points for differentiating policy recommendations, not only related to region or income level, but relative to a country's equity profile. In this way, this research creates a more comprehensive and evidence-based roadmap toward SDG 4.2 globally.

6. Conclusions

Overall, the current study analyses global equity in ECE using a multi-method approach by examining all countries with ECE indicator data compiled by UNESCO from 1998 to 2024. By combining longitudinal trend analysis, cluster analysis, and global and regional comparisons between girls and boys, this study provides a multi-dimensional view to demonstrate variation in access and inclusion across countries. The integration of inequality indices (*Gini* and *Theil*) and autoregressive dynamics with structural breaks extends the methodological scope of comparative education by grounding equity analysis in formal mathematical tools. This bridges the interface of applied statistics, dynamical systems, and social science, aligning with the journal's mission to highlight the methodological role of mathematics across disciplines. The results indicate that, generally, there have been broad improvements in global ECE enrollment. However, considerable variation exists concerning access and equity by gender, wealth, and region. The cluster analysis indicated that even *high levels of enrollment* could mean *low levels of equitable participation*. This is a significant consideration that typological approaches (such as those in this study) can uncover. These findings should be able to provide better informed pathways for educational policymakers and planners as they continue to seek common ground in addressing national strategies aligned to Sustainable Development Goal 4.2.

While the research made some contributions, it is imperative to acknowledge several limitations. First, the final analytical sample only included 16 countries as strict criteria were applied to data completeness. While it offered regional diversity, it also limited the generalizability of the cluster typologies. Second, the final analyses reported on quantitative indicators only; they did not include qualitative policy or institutional contexts that could be just as or more informative in evaluating ECE outcomes. Third, the potential bias present in the analysis of the data was influenced by the reliance on countries' official self-reported data. This assumes that there is a reasonably consistent definition of pre-primary education across all countries. Lastly, the study neglected a fourth critical dimension of equity-quality; specifically, elements related to teacher qualifications, curricular content and design, which might not be available in the current database selection.

The study findings also offer implications for researchers and policymakers. First, for policymakers, the scalar cluster profiles identified in the analysis suggest that a "***one-size-fits-all***" approach to equity in ECE would be inadequate. Countries with low access, but high parity (Cluster 2) may benefit from targeted expansion efforts, while those with high access, but persistent disparities (Cluster 1) should focus on inclusive policy reforms, especially for marginalized populations. These regions should pursue national policy reform and make pedagogy more inclusive of all regions, wealth groups and marginalized populations. Developments in this area through equity in ECE would be necessary to reduce elitism. This is especially for vulnerable groups of children and their families. Furthermore, the cluster analysis profiles could also help assess and prioritize technical assistance to governments for planning and meeting their objectives and identifying concrete resource allocations. Second, for future research, the study clearly offered methodological means of using indicators data to develop typologies of data in comparative education contexts. This was if extended to be more inclusive of qualitative perspectives and ideation and outcomes-based indicators. Future studies should take into account the quality of classroom environments, parental engagement, or institutional governance within access. Hence, provide a more complete picture of equity in ECE. They could also provide information on pathways that include priorities for sustainability. Lastly, replicating the cluster analysis with updated or broader datasets can ultimately help validate the typologies and track changes over time, particularly in the post-pandemic context. In this sense, the paper demonstrates how mathematical formulations; through clustering criteria, inequality measures, and autoregressive models, can serve as replicable frameworks for evaluating Sustainable Development Goal 4.2 and similar global challenges where equity and dynamics intersect.

6.1 Managerial Implications

The findings of this study carry several implications for education managers, policymakers, and organizational leaders responsible for early childhood systems:

- **Strategic Resource Allocation** - The three cluster typologies provide managers with a portfolio view of system performance. Countries with low access but balanced parity (Cluster 2) need investments in infrastructure, workforce, and outreach, whereas those with high access but persistent gaps (Cluster 1) require targeted inclusion strategies for disadvantaged populations.

- **Equity Monitoring as Management KPI** - By combining Gini and Theil indices with UNESCO parity ratios, managers can translate equity into measurable performance indicators (KPIs). This allows equity to be monitored alongside more traditional metrics such as enrollment or completion rates, strengthening accountability systems.

- **Risk and Resilience Planning** - The autoregressive analysis highlights the persistence of shocks ($\varphi \approx 0.9$) and the lasting effect of COVID-19 on ECE participation. For managers, this emphasizes the need to build resilient systems that can absorb crises, with contingency plans and flexible financing mechanisms.

- **Evidence-Based Differentiation** - The cluster typologies support a move away from "one-size-fits-all" strategies. Managers can tailor interventions to specific profiles, ensuring resources are applied where they will have the greatest marginal impact on equity.

6.2 Implications for Southeast Asian Context

For Southeast Asia, the results are particularly relevant given the region's diversity in educational development and governance structures:

- **Varied Equity Profiles** - Countries such as the Philippines and Vietnam have expanded ECE access rapidly, but disparities persist in rural or low-income groups. Others, like Cambodia or Lao PDR, continue to struggle with both access and parity. The cluster framework can help policymakers

benchmark their systems not just against income peers but also across equity typologies.

- **Gender and Cultural Dimensions** - Regional traditions influence gender participation differently. In some contexts, cultural norms encourage girls' early enrollment, while in others, caregiving expectations reduce their participation. This underscores the need for culturally responsive management strategies that account for household expectations and community practices.
- **Cross-National Learning** - ASEAN initiatives such as the Southeast Asian Ministers of Education Organization (SEAMEO) provide platforms for policy sharing. The typological and inequality indices presented here can serve as common metrics for cross-country dialogue, fostering collective progress toward SDG 4.2 in the region.
- **Policy and Leadership Development** - For managers and administrators, adopting data-driven approaches to track equity helps align ECE with broader human capital strategies. This is especially important as Southeast Asian economies emphasize inclusive growth and labor market readiness.

Declaration of AI Use in the Preparation of the Manuscript: In the preparation of the manuscript, the authors used Wordtune and Grammarly to assist in refining the manuscript's grammar and clarity. We then carefully reviewed all changes and take full responsibility for the final version of the text.

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