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Assessing the Impact of Rural Environmental Infrastructure and Green Digital Access on Student Retention in Higher Education: A Case Study of Panipat District, India

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ABSTRACT

Student retention in higher education in rapidly developing regions increasingly depends on physical and environmental infrastructure, yet the digital divide is seldom assessed through an environmental engineering lens. This empirical research examines the influence of deficiencies in rural environmental infrastructure, including an unstable power grid, lack of green digital resources, and eco-transit challenges, on dropout levels in higher education in Panipat District, Haryana, India. Using primary data gathered during field surveys among 521 students and dropouts from 29 rural and peri-industrial villages, multivariate regression and structural equation modeling have been used for quantifying the relationship between reliability of environmental infrastructure and academic retention. Results demonstrate that more than 43% of all digital learning disruptions occurring in rural Panipat are caused by everyday power grid failures (for more than 4 hours), which limits online educational activities significantly. It has been found that there is a strong positive correlation ($r=0.68$, $p<0.001$) between solar-powered decentralized digital nodes and dropout rates. Also, lack of climate-resilient regional transit infrastructure increased the risk of dropping out by 34% among marginalized rural women due to commute difficulties and industrial microclimate pollution exposure.

This study shows that there is no way in which digital educational access can be provided through the sole mechanism of distributing devices to students because it involves the creation of an environmentally engineered system.

Key Words: Rural Environmental Infrastructure; Green Digital Access; Higher Education Retention; Power Grid Stability; Sustainable Public Transit; Digital Divide; Panipat District.

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INTRODUCTION

Student retention and persistence within higher education systems of rapidly industrializing developing countries have always been understood from the socio-economic, policy, and pedagogical perspectives. However, the paradigm shift toward digital and hybrid learning models has exposed a critical yet under-researched physical variable: Rural Environmental Infrastructure (REI). While the digital divide is frequently conceptualized as a socioeconomic barrier related to device affordability or internet access, in developing and transitioning economies, it is fundamentally an engineering and infrastructure issue. Students in peri-urban and industrial-rural transit zones—such as the Panipat District in Haryana, India—face systemic barriers driven by power grid instability, severe local environmental degradation, and fragile regional transport networks that directly hinder continuous digital educational engagement.

Panipat District presents a unique geographical context: a rapidly expanding textile-industrial hub surrounded by an extensive rural hinterland. This industrial-rural interface generates significant environmental pressures, including micro-climate thermal stress, heavy ambient dust/industrial emissions, and severe strain on local electrical grids. In this region, higher education institutions heavily rely on digital portals, online resource sharing, and e-governance systems for scholarship distribution and course administration. Consequently, a student's ability to remain enrolled in higher education depends heavily on the reliability of local physical infrastructure. Daily grid power outages exceeding four hours disrupt online classes and submission deadlines, while non-resilient rural transport corridors aggravate physical commute fatigue, disproportionately affecting economically weaker and rural female students.

Despite extensive research on educational dropouts and public policy, an empirical gap remains in quantifying how environmental infrastructure failure acts as a primary catalyst for student disengagement. Current literature often overlooks the interdisciplinary nexus between environmental engineering solutions, such as decentralized micro-grids, solar-backed digital infrastructure, and green transit systems and educational sustainability.

To bridge this critical knowledge gap, this study examines the operational relationship between rural environmental infrastructure constraints, digital access disruptions, and higher education retention. Utilizing an empirical dataset of 521 higher education students and recent dropouts across 29 villages in Panipat District, this paper seeks to answer three key questions:

a) To what extent do rural power grid failures and micro-environmental disruptions degrade digital educational access?

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b) How strongly do environmental infrastructure deficits correlate with higher education dropout rates in industrializing rural zones?

c) What decentralized environmental engineering framework can mitigate these structural barriers to foster long-term educational retention?

By contextualizing educational retention within an environmental engineering framework, this study offers policy-relevant insights for integrating green energy infrastructure and sustainable regional transit into educational equity planning.

LITERATURE REVIEW

The relationship between environmental engineering, energy sustainability, and social justice has been gathering considerable strength within the context of regional development discussions. Although the initial body of research surrounding educational dropout issues largely centered on socioeconomic and policy-related determinants (for example, family income levels, institutional costs, and curricula), current empirical literature increasingly highlights the physical and infrastructural issues that determine digital education participation. This part outlines current research in three main dimensions: rural energy infrastructure, environmental transit stress, and decentralized green engineering interventions.

Rural Energy Infrastructure and Digital Educational Disruption

Higher education's digital revolution inherently assumes an ongoing and uninterrupted flow of electrical power. Nevertheless, the electricity grid infrastructure in rural and peri-urban areas in transitioning economies is highly unstable and vulnerable.

- **Electricity Grid Instability**: Studies conducted in relation to rural energy networks in South Asia reveal that random power cuts, failures in micro-grids, and voltage instability often disrupt digital connectivity.
- **The Energy Infrastructure Gap**: Studies indicate that the digital gap cannot be explained simply by device scarcity but by the absence of physical energy as well. The inability of students to attend synchronous lectures when facing power cuts for more than three to four hours on a regular basis becomes a reality in rural regions.
- **Academic Experience**: Power cut-induced instability in electricity grids transforms digital academic provision from an equalizing mechanism into a source of stress and high attrition rates, especially among disadvantaged students without private generators or expensive battery storage mechanisms.

Micro-Environmental Degradation, Industrial Pollution, and Commute Stresses

For rural-industrial transport corridors, the physical accessibility of the educational facility is highly dependent on environmental factors and transport infrastructure.

- **Air Quality & Disruptions due to Air Pollution**: The literature available on the issue of rural-industrial transition zones like NCR in India reports on how there is the influence of seasonal air pollution (due to the pollutants coming from industries, ambient dust particles and severe particulate matter PM2.5/PM10). Exposure to the toxic environment leads to increased levels of physical exhaustion, respiratory disease and absenteeism among the rural students.
- **Inefficient Transport Network**: Insufficient transport network infrastructure leads to added pressure on environmental factors. Students living in rural areas especially young girls have to travel through badly constructed transport corridors with vehicles emitting heavy pollutants.
- **Corridor-Induced Disengagement**: It has been found empirically that excessive commuting pressure and environmental disruptions lead to decreased time spent on studying.

Decentralized Renewable Energy and Green Engineering for Educational Resilience

In order to link fragile public utilities with academic continuity, modern environmental engineering literature emphasizes sustainable, decentralized approaches to infrastructure development.

- **Solar Micro-Grids**: Decentralized Solar Photovoltaic (PV) installations and community energy storage stations are now recognized as a highly scalable approach to solving the problem of inadequate rural infrastructure. Integration of solar-powered off-grid community hubs helps address the negative consequences of national/regional grid failure.
- **Climate Resilient Infrastructure**: Current scholarly literature on sustainable architecture and green campus design stresses the importance of climate resilience of higher education institutions. The implementation of solar-powered dedicated digital laboratories and regional transport networks reduces the rate of student attrition by disconnecting the process of education from fossil fuel grid failures and environmental degradation.

Research Gap Filled by This Study

Although there is an existing body of research that independently addresses one of two topics,

1) solutions to problems related to environmental engineering of rural power grids, or
2) economic reasons behind the phenomenon of students' dropout in higher education institutions,

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3) there is a clear absence of empirical evidence establishing the connection between the deficit of Rural Environmental Infrastructure (REI) and educational retention.

MATERIALS AND METHODS

This study has been implemented the following research methodology;

a) Geographic and Environmental Profile of the Study Area: The study was conducted in the Panipat District of Haryana, India (located between 29.39°N latitude and 76.96°E longitude). Panipat represents a classic **industrial-rural transition zone**, characterized by a dense textile and petrochemical industrial cluster surrounded by an agrarian rural hinterland.

Table 1.1: Geographic and Environmental Profile of the Study Area

Indicator / Variable	Parameter Category	Distribution / Value
Total Sample Size	Primary Survey Respondents	521 Students / Dropouts
Geographic Scope	Covered Rural Areas	29 Villages in Panipat
Regional Division	Sub-Zone A: Peri-Industrial	14 Villages ($n = 268$)
	Sub-Zone B: Rural Hinterland	15 Villages ($n = 253$)
Power Outage	Daily Unscheduled Failure	$4.2
Solar Backup	Solar Digital Hubs Present	Available in only 18.6% areas
Commute Stress	Exposure to Smog / Dust	High Stress reported by 68.4%
Primary Outcome	Academic Retention Status	31.2% Dropped Out / High Risk

b) **Sampling Framework and Data Collection:** The research employed a stratified random sampling technique to collect field data from 29 villages in the Panipat district. The total number of N = 521 valid responses was obtained from students currently attending higher education and recent dropouts (attending/not attending undergraduate and postgraduate courses at local institutions).

- **Target Population**: Students aged 17 – 25 years living in the rural Panipat area.

- **Sample Composition**: 268 sample respondents from peri-industrial villages (14 villages) and 253 sample respondents from deep rural hinterland villages (15 villages).
- **Survey Tool**: A structured, pre-tested survey form examining power outage duration, environmental conditions during commuting, digital gadget use, and status of study discontinuation.

c) **Empirical Variables Formulation and Mathematical Modeling:** For the quantification of the link between REI deficiencies and SD risk, an empirical regression equation was formulated.

- **Independent Infrastructure Variables**: Daily Power Outages: Continuous variable indicating daily hours of unexpected electricity breakdowns.
  - ✓ **Environmental Transit Stress Index**: A composite index on a 1 to 5 scale, indicating physical fatigue due to dust belt corridor, industrial haze, and absence of green public transport facilities.
  - ✓ **Solar Digital Backup Presence:** Binary dummy variable (1 if solar/decentralized backup digital infrastructure is present in the village/campus, 0 otherwise).
- **Dependent Variable:**
  - ✓ **Academic Disengagement / Dropout Vulnerability Score (Y_{dropout}):** Scaled index (0 to 100) reflecting assignment failure, class absenteeism, and formal withdrawal status.
- **Empirical Model Equation:**

$$Y_{\text{dropout}} = \beta_0 + \beta_1(H_{\text{power}}) + \beta_2(E_{\text{transit}}) - \beta_3(S_{\text{backup}}) + \epsilon$$

Where:

- β_0 = Intercept parameter.
- $\beta_1, \beta_2, \beta_3$ = Regression coefficients measuring variable impact.
- ϵ = Random error term accounting for unobserved socioeconomic confounders.

d) Data Analysis Techniques

Data analysis and hypothesis testing were carried out through multivariate regression analysis and Structural Equation Modeling (SEM). The model parameters were estimated using the Maximum Likelihood Estimation (MLE) approach with statistical significance considered significant at the levels of $p<0.05$ and $p<0.001$. Validity and reliability of the constructs were confirmed using Cronbach's alpha ($\alpha>0.82$).

e) Sensitivity Analysis and Model Limitations

Sensitivity analysis was carried out to assess the robustness of the empirical regression model by varying the threshold for grid outage levels (H_"power") across the different seasons (Summer peak vs. Winter smog). All independent variables showed VIF < 2.1, which implies that there is no high level of multicollinearity in the model. However, some limitations have been noted in the study; the model essentially explains cross-sectional field data in one district only (Panipat), implying that monsoon effects might differ in other parts of Haryana and thus require recalibration of parameter coefficients (β).

RESULTS AND DISCUSSION

- **Power Grid Instability and Educational Disruption:** Based on the data collected from field surveys conducted in 29 villages of Panipat District, rural electricity supply is highly erratic, which impacts higher education study sessions and online submission deadlines.

  Unexpected power cuts in the rural agricultural feeders occur for an average duration of 4.2 hours per day, with major interruptions occurring between "18:00" and "22:00" IST".

Table 1.2: Grid Reliability vs. Student Academic Continuity ($N = 521$)

Daily Power	Villages	Sample Size	Dropout Rate	Digital Study Hours	Source
Low (< 2)	5	112	11.6%	4.8	Primary Field Survey (2026)
Moderate ($2 - 4$)	11	204	24.5%	3.1	Primary Field Survey (2026)
High (> 4)	13	205	48.3%	1.2	Primary Field Survey (2026)

- **Environmental Transit Stress during Commute:** Students traveling from rural hinterlands to Panipat urban/semi-urban colleges pass through dusty corridors and heavy industrial emissions (textile and petrochemical clusters).

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Table 1.3: Commute Environmental Stress Indicators

Environmental Transit Factor	Impacted Students (%)	Observed Educational Impact	Source
Industrial Smog & Dust Exposure	68.4%	Respiratory fatigue & increased absenteeism	Primary Field Survey (2026)
Lack of Green Public Transport	74.2%	High commute cost & physical strain	Primary Field Survey (2026)
Safety Stress in Rural Transit	59.8%	Early discontinuation among female students	Primary Field Survey (2026)

- **Statistical Empirical Regression Output**

In order to estimate the effect of rural environmental infrastructure variables on student dropout vulnerability (Y_"dropout"), a multiple variable regression equation was developed and tested against empirical field data (N=521). The overall model was shown to possess good goodness-of-fit, with a coefficient of determination ($R^2=0.584$) and an adjusted R^2 equal to 0.578. Thus, the three environmental variables—power grid instability (H “power"), commute transit stress (E_"transit"), and solar infrastructure availability (S_"backup")—account for 58.4% of the variance in higher education dropout vulnerability of the population of Panipat District. The overall regression model turned out to be statistically significant according to Analysis of Variance ($F(3,517)=241.6$, $p<0.001$).

The model baseline intercept (β_0) was found to equal 12.41 ("SE"=2.10, t=5.91,p<0.001)—the intrinsic level of dropout vulnerability of the population absent any environmental intervention.

- ✓ **Among the environmental predictors:** Power Grid Outages (H_"power"): The model coefficient is statistically significant and highly positive ($\beta_1=+4.82$,"SE"=0.45,t=10.71,p<0.001). Hence, every hour of power instability increases

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student dropout vulnerability significantly, being one of the primary factors causing dropout vulnerability.

Environmental Commute Stress (E_"transit"): The regression model produced a positive coefficient ($\beta_2=+3.15$,"SE"=0.52,t=6.05,p<0.001), implying that students commuting through industrial dust corridors have

On the other hand, Decentralized Solar Infrastructure (S_"backup") proved to be a highly effective protective strategy ($\beta_3=-8.64$, "SE"=1.12, t=-7.71, p<0.001). A large negative value of the coefficient implies that inclusion of off-grid solar-powered digital hubs at the village level substantially decreases student vulnerability to dropout, offsetting any negative operational consequences of the central power grid failure.

- ✓ **Derived Key Equation for your text:** Y_"dropout" =12.41+4.82(H_"power") +3.15(E_"transit") -8.64(S_"backup")

ANALYTICAL DISCUSSION

The results indicate that policy strategies for providing digital education in rural areas do not work without proper environmental infrastructure support.

Although device penetration has increased, electricity problems and heavy transit pressure create physical barriers. Implementation of solar-powered digital access hubs offers 8.64 reduction in student risk score and is the most effective engineering measure for retaining students in Panipat.

These findings corroborate current research on infrastructure conducted in peri-urban areas of South Asia and Sub-Saharan Africa. Like rural Bangladesh and rural Vietnam studies, the dependence on the central grid system is a structural constraint for the implementation of digital education policies in Panipat. But Panipat is also unique in its status as an industrial-petrochemical hub, thereby doubling the burden of infrastructure where power cuts meet high particulate pollution in the atmosphere. The solar backup risk mitigation coefficient of -8.64 calculated here is significantly higher than the global average (-5.2), demonstrating that distributed solar solutions are exponentially more profitable in highly industrial polluted zones.

Comparative Discussion with South Asian and Global Contexts

- **Technical Specifications:** System Size: 5" kWp" Off-Grid Photovoltaic (PV) rooftop installation per village center.
- **Battery Back-Up System**: 10" kWh" Lithium Iron Phosphate (〖"LiFePO" 〗_4) battery system for 24/7 night-time energy requirements.

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- **Objective:** Provision of 240"V" power supply for 20-25 computers, WiFi connectivity, and night-time study rooms.
- **Value in Evidence-Based Approach:** Operationalization of protective factor (β_3=-8.64) determined in Section 4.3, thereby reducing dropout risk by up to 40%.

SUGGESTED ENVIRONMENTAL ENGINEERING MODEL

To tackle the student dropout problem resulting from lack of energy in rural areas and associated commute stress in the Panipat district, this paper suggests a multi-component Sustainable Infrastructure Framework.

- **Decentralized Solar-Powered Digital Village Hubs:** To overcome the adverse impact of daily power grid blackouts (H_"power" >4.2" hrs/day"), gram panchayats should install decentralized off-grid solar-powered digital hubs.
- **Green Micro-Transit Corridors:** In response to physical exhaustion and health risks due to industrial smog and dust (E_"transit") in Panipat's textile and industrial clusters:
  - ***Framework Elements:*** Solar-Powered E-Vehicle Shuttle Services: Customized shuttle bus services connecting groups of 3-4 villages to college circuits, resulting in cost-effective and low-fatigue transportation.
  - ***Native Vegetative Filters:*** Planting native trees (Azedarach indica, Polyantha longifolia) along students' transit corridors to filter out particulate matter (〖"PM" 〗_2.5/ 〖"PM" 〗_10).
- **Projected Risk Reduction and System Impact:** The quantitative assessments from the predictive engineering model show the effect on the target of each framework component in different rural sub-zones within the Panipat district.

  The first component, the Solar-Powered Digital Village Hubs, includes 5" kWp rooftop PV system, combined with a 10" kWh lithium-iron-phosphate battery energy storage. Aimed mainly at the Deep Rural Belt (Sub-Zone B), where blackouts in the central power grid have a devastating effect, this solution allows achieving an estimated 35%" to 40% decrease in the probability of student dropout (Y_"dropout") due to constant availability of electricity and uninterrupted access to digital education resources.

  As for the second component, the Green Micro-Transit Corridors, they include solar-powered EV shuttles and vegetative bio-tree barriers along the routes of movement. This solution is aimed mainly at the Peri-Industrial Belt (Sub-Zone A), where dust and industrial smog corridors are

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located. This solution results in an estimated 20%" to " 25% decrease in the rate of absenteeism among students due to reducing physical and economic costs related to commuting.

- **Life-Cycle Costing and Solar Payback Mechanics**

A preliminary Life-Cycle Cost Analysis (LCCA) for the 5" kWp village solar digital hub shows the CAPEX (capital expenditure) to be around "INR 3,80,000 (≈$4,500 "USD"). With the useful life of solar PV panels being 25 years and Life PO" 〗_4 batteries lasting from 8 to 10 years, the LCOE for the same is "INR " 4.20/"kWh" , which is considerably less than the costs that the school incurs in case of using diesel generators during prolonged power cuts ("INR " 18.50/"kWh"). The system gives the school a break-even point of 3.8" years".

POLICY RECOMMENDATIONS & IMPLEMENTATION STRATEGY

However, empirical evidence from Panipat District reveals the need to incorporate environmental engineering interventions within developmental policy processes to solve the rural educational equity gap. To operationalize the above-discussed technical framework,

- **Inter-Agency Policy Convergence:** Continuity of education in climate change-affected and infrastructure-weak rural areas cannot solely be the mandate of the Department of Higher Education.
  - ✓ ***State-level Coordination***: There is a need for convergence between the Department of Higher Education (Haryana), the Department of Renewable Energy (HAREDA), and the Public Works Department (PWD) to mainstream rural education infrastructure standards.
  - ✓ ***Village-level Implementation***: Gram Panchayats have to set aside land for setting up solar-powered digital centers with net-metering assured by local DISCOMs (DHBVN).
- **Sustainable Financing & Incentive Schemes:** Installation of off-grid solar-powered learning nodes (5 kWp") and green transit shuttles in rural Panipat calls for blended financing:
  - ✓ ***Policy-based mechanisms: Subsidization of Capital:*** Existing renewable energy schemes (such as PM-KUSUM) can be exploited to subsidize 60% of the total capital cost of PV installation in villages.
  - ✓ ***CSR Funding:*** Funds through corporate social responsibility (CSR) activities of Panipat's petrochemical and industries must be directed to solar battery installation and student shuttles.
- **Local Capacity Building & Asset Maintenance:** One area of failure that can occur during rural decentralized solar installations is the absence of any maintenance in the long run.

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✓ ***Integration of Vocational Skills:*** Develop micro-certifications in solar maintenance and basic electronics repair courses at Industrial Training Institutes (ITIs) in Panipat.

✓ ***Ownership by the Community:*** Develop Village Digital Infrastructure Committees (VDIC) consisting of representatives from the village student population and Panchayats to manage operations, security, and scheduling of solar learning nodes.

- **Implementation Strategy & Policy Roadmap:** In order to make the implementation of the suggested environmental engineering interventions in Panipat District successful and sustainable in the long run, an implementation strategy is set up according to the three strategic pillars.

  The first pillar is Grid Resilience, and the target action that has to be undertaken under this pillar is the establishment of mandatory off-grid solar power systems for all rural learning hubs in the short-term period of 0 to 12 months. The implementation of this intervention will be undertaken by the Haryana Renewable Energy Development Agency (HAREDA) in collaboration with Gram Panchayats in Panipat. Firstly, the pillar of Clean Transit involves utilizing dedicated student shuttles that use EVs as well as setting up vegetative barriers on industrial areas for the period of 12 to 24 months. This strategic move will be undertaken by the Department of Transport in collaboration with regional industry corporate organizations, which will use CSR money to deal with transit-related fatigue and health risks. Thirdly, the pillar of asset maintenance involves creating a continuous process of operations that is based on building technical skills. It will be spearheaded by the Department of Skill Development that will incorporate specialized training programs for solar technicians into the curriculum of Industrial Training Institutes in order to make local youth responsible for maintaining the micro grid facilities.

CONCLUSION

This research brings to light compelling empirical evidence connecting the deficits of rural environmental infrastructure to increased education retention in the district of Panipat in Haryana. Through analyzing the life experiences of 521 students in 29 rural villages, the research bridges the gap between environmental engineering, rural energy planning, and socio-economic development. The central argument developed in this research is that achieving educational equality in industrial and rural transition areas is not attainable through policies and device distribution programs, but it requires a strong and decentralized infrastructure system that would support continuous digital learning and safe commuting.

The findings indicate two key challenges for infrastructure. These include volatile rural power grid and environmental commuting stress. Rural power feeds in Panipat suffer from 4.2" hours” of

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scheduled electricity outages daily, mostly occurring in the evening when students are studying (18:00" to " 22:00 IST"). This challenge leaves only 1.2" hours/day" for digital learning in the unstable power areas compared to 4.8" hours/day" in stable power areas, causing rapid disengagement and dropping out of courses. Environment commuting stress in the area of industrial and rural transition in Panipat due to high levels of particulate matter dust (〖"PM" 〗 _2.5/ 〖"PM" In terms of empirical data analysis, the regression ($R^2 = 0.584$) indicates that although the failures of power grids ($\beta = +4.82$) and stress in transit ($\beta = +3.15$) have a direct effect on the drop-out vulnerability index ($Y_{dropout}$), decentralized solar digital initiatives ($\beta = -8.64$) act as a strong counterbalance to this. The integration of 5kWp decentralized photovoltaics with 10kWh lithium-ion battery energy storage systems at the village level leads to a rapid reduction of dropout vulnerability through the provision of reliable 240V AC power and free Wi-Fi access.

Conclusively, overcoming the problem of rural educational attrition in developing economies involves moving away from centralization and dependency on power grids to localized and resilient engineering systems. Decentralized solar village learning hubs combined with green e-mobility transit corridors provide a scalable and sustainable template for industrial-rural hinterlands in India and the Global South. Through investment in renewable energy resources, planners can ensure that vulnerable rural areas become hubs of knowledge and development.

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