HUMAN CAPITAL AND CIRCULAR ECONOMY: A TECHNICAL REPORT ON ACTIVE RECYCLING AGENTS (ARAS) IN SÃO PAULO

1. INTRODUCTION

Brazil faces pressing challenges in terms of solid waste governance. Despite formal advances in policy, most notably the National Solid Waste Policy (PNRS) (Brasil, 2010), landfills remain overcrowded, and the recycling rate lags behind the national targets. The PNRS calls for a 50% increase in recycling within two decades and mandates shared responsibility among waste generators, collectors, and recyclers. However, implementation bottlenecks persist, especially at the community level, due to fragmented coordination and limited local infrastructure (ABRELPE, 2022).

As previously stated (Hollnagel & Araújo, 2023), Active Recycling Agents (ARAs) operate informally in São Paulo's peripheral neighborhoods, where residential waste generation is the highest. Despite their crucial role in connecting waste sources to reuse opportunities, they often lack formal recognition, training, and integration into public systems (De Paula et al., 2016). Addressing waste and promoting eco-efficiency thus requires technological solutions as well as institutional and human capital development (Ghisellini et al., 2016; Stahel, 2016).

From a theoretical standpoint, this study draws on seminal models of economic growth to frame the role of human capital in sustainability transitions. Lucas (1988) developed an endogenous growth model in which human capital is the central engine of sustained economic progress, largely through *spillovers* and organizational learning. Additionally, Mankiw, Romer, and Weil (1992) extended the Solow model to include human capital as a factor of production, proposing *conditional convergence* between economies. In contrast, Nelson and Phelps (1966) argue that human capital enhances the ability to absorb and apply new technologies, especially through *education-driven diffusion*.

These frameworks offer complementary insights into how education, experience, and institutional quality affect productive performance—not only in terms of GDP but also in terms of environmental efficiency and innovation, as displayed in Frame 1.

Frame 1. Economic Growth Models Framing the Role of Human Capital in Sustainability Transitions

Aspect	**Lucas (1988)**	**Mankiw et al. (1992)**	**Nelson & Phelps (1966)**
Model Type	Endogenous	Extended Neoclassical	Technological Diffusion
Focus	Human capital accumulation	Physical + human capital	Education and adaptation
Sustained Growth?	Yes	No (limited growth)	Not directly
Policy Implication	Continuous education	Factor accumulation	Educational quality
Technological Innovation	Internal to system	Exogenous	External absorption

Source: the authors

These models can be directly applied to the **circular economy (EC)** as follows:

- Lucas (1988) found that human capital spillovers and organizational learning accelerate green innovation and circular design strategies.

- Mankiw et al. (1992) found that human capital explains cross-country differences in clean technology adoption and production efficiency.
- Nelson and Phelps (1966): The capacity to absorb sustainable technologies is strongly conditioned by educational quality and workforce training.

Recent research has built on these theories to explore the interface between **human capital, economic growth and circularity**. Studies (Frame 2) demonstrate how knowledge, education, and organizational learning enable material reuse, eco-design and waste reduction.

Frame 2: Recent Literature Linking Human Capital, Growth, and Circular Economy

Author(s)	**Main Insight**	**Theoretical Link**
Zafar et al. (2022)	Human capital boosts circular performance in emerging economies.	Aligns with Lucas (1988) on knowledge spillovers.
Rizos et al. (2016)	Technical knowledge enables SMEs to adopt CE practices.	Echoes Nelson & Phelps (1966) on technology absorption.
Ghisellini et al. (2016)	Knowledge drives eco-efficiency and green transition.	Supports all three frameworks.
Leal Filho et al. (2019)	University education shapes sustainability behaviors.	Based on human capital as a cultural asset.
D'Amato et al. (2017)	Green economy shaped by innovation and policy.	Aligns with Lucas (1988) and MRW.
Bilal et al. (2020)	Applied knowledge reduces textile industry waste.	Reflects spillover and absorption dynamics.
Geng et al. (2012)	Human and institutional capacity shape CE efficiency.	Nelson & Phelps (1966) lens.
Bocken et al. (2016)	Business models and eco-design rely on learning.	Lucas (1988) and Nelson-Phelps.
Stahel (2016)	Circular models rely on knowledge feedback loops.	Aligns with systems thinking and capital theory.

Source: the authors

Together, these insights offer a robust conceptual foundation for analyzing how investments in **education, skills, and institutional design**—particularly among informal agents such as ARAs—can drive both economic growth and environmental sustainability.

2. CONTEXT UNDER INVESTIGATION

This study adopts a microeconomic perspective on waste dynamics, linking the Production Curve (PC) to Waste Generation (WG) and Recycling Curves (RC). Waste and recycling are directly tied to production efficiency; better processes reduce waste and expand reuse potential. The role of human capital is central, as highlighted by Lucas (1988), who views it as the engine of endogenous growth; Mankiw et al. (1992), who include it as a key input explaining differences in performance; and Nelson and Phelps (1966), who emphasize its role in absorbing new technologies. For ARAs, this means that training and skill development enhance their ability to sort and reuse materials effectively.

Complementing this, Arrow's (1962) concept of learning by doing shows how daily practice strengthens knowledge and resilience. Together, these perspectives suggest that investing in ARAs' human capital and institutional support improves waste governance and advances circular-economy outcomes.

3 PROBLEM-SITUATION DIAGNOSIS

3.1 PRODUCTION CURVE FOUNDATIONS

The Production Function is a theoretical construct from classical economic theory used to estimate the maximum output achievable given specific combinations of labor and physical capital. Over the past few decades, this model has evolved to incorporate human capital, research and development (R&D), and technological progress as key determinants of productive capacity growth. Influential works such as Lucas (1988), Mankiw, Romer, and Weil (1992), and Nelson and Phelps (1966) demonstrate how these factors shift the production curve outward, signaling productivity gains.

Importantly, Arrow's (1962) concept of *learning by doing* shows how productive experience accumulates as tacit knowledge, leading to sustained efficiency improvement. Later, Hall and Jones (1999) emphasized the critical role of institutional quality and technological adoption in explaining international productivity differentials. These insights are vital for understanding how more efficient production processes inherently reduce waste generation and expand recycling capabilities as natural outcomes of innovation.

3.2 GENERATION AND RECYCLING CURVES: A THEORETICAL EXTENSION

Building on this theoretical foundation, we extended the logic of the production curve to waste dynamics. The Waste Generation Curve (WG) and Recycling Curve (RC) are proposed as parallel functions influenced by the same systemic variables: human capital, institutional quality, and innovation.

The key hypothesis is that *for any given increase in production capacity, a better-trained and institutionally supported workforce will generate less waste (WG shifts down) and recycle more (RC shifts up).*

Thus, investments in education, training, and infrastructure, particularly for actors such as Active Recycling Agents (ARAs), contribute not only to productive efficiency but also to material circularity. These effects create a positive feedback loop in which economic growth does not necessarily imply ecological degradation.

3.3 THE BRAZILIAN PRODUCTIVITY PARADOX

Brazil's productivity has remained stagnant for over 40 years, with an average annual growth of only 0.6%, among the lowest globally. This stagnation is not primarily due to labor performance but to structural constraints, including:

- Expensive and inefficient logistics (e.g., overreliance on road freight instead of rail),
- High energy costs due to complex taxation and subsidy systems,
- Excessive bureaucracy in business operations and trade,
- There is a deficit in technical education compared to international standards.

These bottlenecks collectively constrain Brazil's ability to reduce waste generation and to scale up recycling. Poor infrastructure and limited institutional support significantly reduce the capacity of even the most motivated ARAs to operate effectively.

3.4 WORKFORCE QUALIFICATION AND RECYCLING EFFICIENCY

As noted by Pastore (2004, p. 36) in the Brazilian context:

> "*Mastering specific work skills is fundamental to productivity. Modern work demands the ability to think critically. It's not just about having information but knowing how to use it.*"

This perspective underscores the importance of investing in targeted ARA training. Empowering them with technical knowledge and logistical tools is critical for improving the quality of waste triage, reuse coordination, and circular integration. So, well-trained ARAs act not only as collectors but as system integrators capable of linking waste generators to reuse markets. Their capacity to identify recyclable values, manage materials, and collaborate with industry and government actors is vital for the transition toward a functional circular economy.

3.5 POLICY AND SYSTEMIC IMPLICATIONS

The National Solid Waste Policy (PNRS, Brasil, 2010) sets a target to increase recycling by 50% within 20 years; however, real-world implementation remains hindered by last-mile inefficiencies and a lack of coordination at the community level (Hollnagel et al., 2024). ARAs, as informal but essential systemic actors, operate at the interface of waste generation and reuse. However, they are rarely incorporated into formal public policy and face significant legal, infrastructural, and technological barriers (De Paula et al., 2016).

Data from IBGE (2020) and ABRELPE (2022) were used to proxy municipal human capital levels and estimated recycling rates, forming the empirical basis for the econometric analysis presented in this study.

4. PROPOSED INTERVENTION

This study employed a quantitative methodology utilizing simulated data informed by public benchmarks and statistical trends from official sources. We conducted a cross-sectional analysis of five major municipalities in São Paulo. Human capital was proxied by education and demographic indicators available through the IBGE datasets (2020), while recycling estimates were aligned with ABRELPE's annual reports (2022).

The hypothesis tested was: 'Higher human capital leads to higher recycling rates.' The core empirical strategy involves estimating a simple linear regression model, where the dependent variable is the municipal recycling rate and the independent variable is the level of human capital.

$$\textit{Recycling Rate\_i} = \beta_0 + \beta_1 \times \textit{Human Capital\_i} + \varepsilon\_i$$

Recycling Rate: The percentage of total waste recycled in locality i. It is the dependent variable that represents the outcome we aim to explain.
β_0 (Intercept): The baseline recycling rate when Human Capital = 0. This anchors the regression line.
β_1 (Coefficient): Measures the marginal effect of Human Capital on the recycling rate. A positive β_1 means that as education/skills increase, the recycling rate also tends to rise.
Human Capital: A proxy variable for the level of education, training, or skill availability in locality i Examples include average years of schooling or municipal education index.
ε_i (Error term): Captures all other unobserved factors that affect the recycling rate but are not included in the model, such as infrastructure, awareness campaigns, or policy enforcement.

The objective of this model is to assess how variations in human capital influence recycling performance across different local contexts in São Paulo (Brazil). In this sense, five municipalities were selected based on their demographic significance and economic diversity: São Paulo, Campinas, Santos, Ribeirão Preto, and São José dos Campos.

5. RESULTS OBTAINED

The proposed interventions are closely aligned with the United Nations Sustainable Development Goals (SDGs), delivering multidimensional benefits:

- **SDG 11 – Sustainable Cities and Communities**, the initiatives are expected to reduce illegal waste disposal and enhance the overall environmental quality of urban areas.
- **SDG 12 – Responsible Consumption and Production**, they promote material reuse, circular resource flows, and production efficiency.
- **SDG 13 – Climate Action**, the circular strategies contribute to lowering carbon emissions through waste reduction and longer product life cycles.
- **SDG 8 – Decent Work and Economic Growth**, the formalization and upskilling of Active Recycling Agents (ARAs) foster inclusive and dignified economic participation.
- **SDG 17 – Partnerships for the Goals** by encouraging collaboration among cooperatives, local governments, private sector actors, and non-governmental organizations.

Resulting from this analysis, the linear regression model yielded an R^2 of 0.70, indicating a strong positive correlation. Each 0.1 increase in the human capital index predicts a 10.5% rise in the recycling rate. Table 1 below summarizes the observed vs. predicted recycling rates for the five municipalities.

Table 1. Human Capital and Recycling Performance: Observed vs. Predicted Rates in Selected São Paulo Municipalities

Municipality	Human Capital Index	Observed Recycling (%)	Predicted Recycling (%)
São Paulo	0.75	18.2	20.94
Campinas	0.68	12.5	13.55
Santos	0.72	22.1	17.77
Ribeirão Preto	0.65	9.8	10.38
São José dos Campos	0.70	15.7	15.66

Source: IBGE (2020) and ABRELPE (2022)

6 TECHNOLOGICAL-SOCIAL CONTRIBUTION

This model proposes strengthening the circular economy by empowering Active Recycling Agents (ARAs), improving coordination, and adopting simple technologies. Human capital is central, as training ARAs enhances their ability to sort, reuse, and connect materials efficiently, thereby increasing both the volume and value of recovered resources while promoting social inclusion and sustainability.

Based on the findings of this study, we propose several public policy recommendations to strengthen circular economy outcomes at the local level:

- **Technical training programs for ARAs**, covering basic chemistry, reverse logistics, classification methods, and pricing strategies;
- The creation of **local reuse centers** that serve as hubs for material exchange, social entrepreneurship, and public education;
- The implementation of **fiscal incentives** to support circular business models, such as tax exemptions for cooperatives and reuse-based enterprises.

Despite these insights, the study also faces certain **limitations**. The econometric model was estimated by using **simulated data** based on public benchmarks, which allowed for preliminary validation of hypotheses but does not yet reflect granular real-world variability. Future research should expand the model using **actual municipal-level datasets**, integrate more explanatory variables (e.g., infrastructure, policy enforcement), and apply it across a broader set of regions for increased robustness and external validity.

Finally, the findings reinforce the role of human capital as a determinant of circular economy outcomes, these actions also support SDGs 11, 12, 13, and 17 and PNRS goals.

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