ACTIVE RECYCLING AGENTS AS CIRCULAR ECONOMY INSTRUMENTS: SYSTEMIC APPROACHES TO SOLID WASTE GOVERNANCE IN BRAZIL

1 INTRODUCTION

Environmental governance in Brazil involves multiple actors—government, enterprises, civil society, and communities—interacting through formal and informal networks (Seixas et al., 2020). Solid waste management exemplifies a "wicked problem" (Rittel & Webber, 1973), demanding systemic coordination across levels and sectors.

Within this framework, Active Recycling Agents (ARAs) operate as nodes linking waste generators with cooperatives, municipalities, industries, and councils. Fieldwork in São Paulo's Campo Limpo district shows how ARAs mediate generator-to-consumer flows by redistributing reusable items such as tiles and paint (Hollnagel, Araújo, & Bueno, 2024). These practices reduce exclusion and provide environmental services in underserved areas.

Despite advances in the National Solid Waste Policy (PNRS; Brasil, 2010), systemic flows remain fragile. General Systems Theory (Bertalanffy, 1968; Checkland, 1999) highlights that recycling depends on **pairing** (alignment between waste generators and reusers) and **ducts** (logistical and informational pipelines). Without pairing, flows do not start; without ducts, they fragment. ARAs help reduce friction and manage temporal misalignments, fostering inclusion and contributing to SDGs 11, 12, 13, and 17 (Hollnagel & Araújo, 2023).

However, ARAs remain informal, underfunded, and largely unrecognized (De Paula et al., 2016). Embedding them into multi-level governance networks—supported by municipalities, consortia, and agencies such as ANA under the Legal Framework for Basic Sanitation (Brasil, 2020)—could create synergies, advance PNRS targets, and strengthen social inclusion. Institutionalization via accreditation, cooperative arrangements, and digital platforms would enhance recycling resilience and accelerate Brazil's transition toward a circular economy.

2 CONTEXTS UNDER INVESTIGATION

The National Solid Waste Plan (PNRS, in Portuguese, *Política Nacional de Resíduos Sólidos*) requires Brazil to expand recovery rates by 50% in 20 years, phase out landfills, and leverage recycling (Brasil, 2010). Applying General Systems Theory (Bertalanffy, 1968; Skyttner, 2005), recycling can be viewed as a systemic flow where ARAs connect households, cooperatives, and reuse markets, intensifying circular economy practices and income generation (Hollnagel & Araújo, 2023; Ghisellini et al., 2016).

Urban configurations, especially in dense cities, constrain ARAs' circulation due to physical and normative barriers (Jacobi & Besen, 2011; Ribeiro & Besen, 2011). Yet endogenous ARAs, such as residents or employees separating higher-value waste in condominiums, illustrate opportunities to integrate circular practices and reverse logistics (Calderoni, 2003; ABRELPE, 2022). Collaborative governance mechanisms are essential to align households, managers, and waste pickers, reducing landfill disposal.

Nonetheless, ARAs lack stable infrastructure, remuneration, and recognition (De Paula et al., 2016; Hollnagel et al., 2024). Systemic bottlenecks stem from temporal mismatches between waste generation and collection and from insufficient ducts, such as vehicles, eco-points, apps, and cooperative networks—that sustain flows. Without these, entropy increases, and recyclable materials are lost.

3 PROBLEM-SITUATION DIAGNOSIS

The literature suggests that ARAs not only act as micro-level managers of complexity—sorting, triaging, and redirecting waste—but also perform governance functions. They are catalysts of community-level partnerships (SDG 17), bridging informal and formal actors and generating new circuits of economic value (Seixas et al., 2020; Hollnagel et al., 2024).

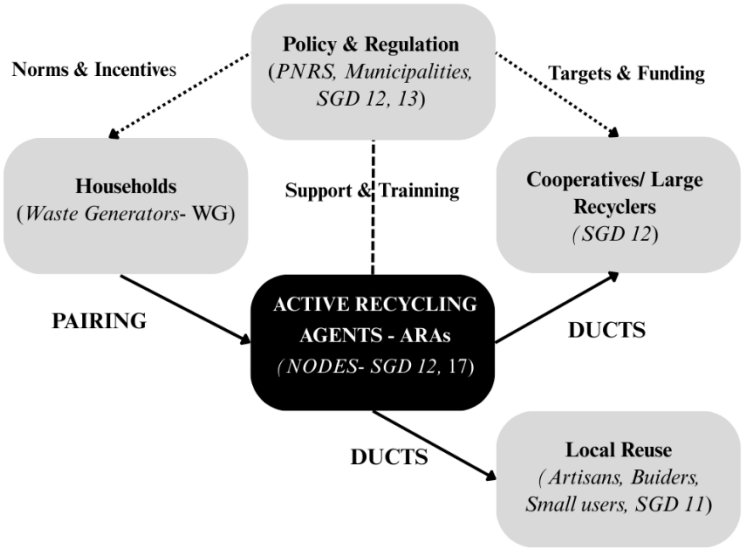
The notion of ARAs as "nodes" echoes the GST principle that systems require mediators to coordinate between subsystems, reducing friction and enhancing adaptive capacity (Checkland, 1999).

Thus, recycling in Brazil can be framed as a complex adaptive system, where:

1. Pairing is a necessary condition for initiating systemic flows.
2. Ducts are structural pipelines that sustain the continuity of flows.
3. ARAs function as systemic couplers that manage complexity, generate income, and strengthen governance networks.

Here is the conceptual diagram (Figure 1) of the recycling system, showing how pairing (Households → ARAs) and ducts (ARAs → Reuse / Cooperatives) sustain flows, while policies (PNRS, municipalities) provide regulation, funding, training and support.

Figure 1 - Conceptual and Systemic Model of Recycling Flow with ARAs as Nodes



Note: Solid lines indicate material flows, and dotted lines represent regulatory and institutional support.
Source: authors.

This study argues that integrating ARAs more explicitly into policy frameworks—as formalized actors supported by municipalities and national programs—can significantly increase recycling efficiency, reduce landfill dependency, and strengthen circular economy governance in Brazil. Policy recommendations include the creation of matching platforms, investment in last-mile logistics, and incorporation of ARAs into local and regional governance networks as a strategy to operationalize the PNRS and accelerate progress toward the 2030 Agenda.

4 PROPOSED INTERVENTION

Solid waste management constitutes a "wicked problem," characterized by interdependent challenges that cannot be resolved by a single institution. Effective governance

requires the coordinated engagement of diverse actors—public authorities, private enterprises, and civil society—through collaborative and adaptive arrangements.

The proposed mathematical model is based on a set of foundational premises.

- **P1**. The micro-processes required to recycle a significant share of household solid waste demand careful sorting and handling at the local level. Materials must be directed either to collection points or to logistical agents who can accumulate larger quantities for proper downstream processing.
- **P2**. The local reuse of a portion of solid waste generates alternative income streams for Active Recycling Agents (ARAs) and end-users of these materials, such as artists, painters, and construction workers. This synergy activates a network of actors across different regions of the country, each shaped by its own geographic, demographic, economic, and social specificities.
- **P3**. The recycling system can be conceptualized as comprising major "arteries" (large cooperatives, transportation fleets, and centralized facilities) that handle high volumes of waste, complemented by a dense capillary represented by ARAs operating locally at the household and neighborhood levels.
- **P4**. The articulation between these governance arteries (GAs) and ARAs generates synergistic effects, increasing the volume of materials recovered and opening new income opportunities for waste pickers and related workers.
- **P5**. The scope of this model is limited to household solid waste, as companies and industries are already regulated under specific legal frameworks, such as the National Classification of Economic Activities (in Portuguese, Classificação Nacional de Atividades Econômicas – CNAE). Therefore, corporate waste generation can be categorized and disciplined *a priori* under existing norms.
- **P6**. The composition of household solid waste is intrinsically complex and temporally variable. Different life-cycle events, such as renovations, maintenance, demolitions, new constructions, demographic shifts, and changes in residents' stages of life, generate distinct waste profiles that require flexible and adaptive responses within the recycling system.

The main goal of the mathematical model is to estimate the generation of household solid waste in a "given area" based on demographic, spatial, and socioeconomic variables. The model is grounded in General Systems Theory (GST), which conceptualizes solid waste flows as a complex adaptive system in which micro-level household practices interact dynamically with macro-level governance structures.

Definitions
A = total area under study.
T = {1,2,3,…,n} = set of categories of solid waste generated in A (e.g., cardboard, plastic, and gypsum).
fl_r = lot/street factor: proportion of A occupied by residential lots versus streets, sidewalks, and other nonresidential areas.
f_o = occupation factor: percentage of residential lots that are actually occupied.
f_v = verticalization factor: percentage of residential occupation that is vertical (apartment buildings).
n_am = average number of floors in an area.
m_r = average number of residents per household.
t_mr = average size of residences (m^2);
r_f = average household income.
AR = occupied area (which may exceed A because of verticalization).

Equations
$AO = A \cdot fl\_r \cdot f\_o$ (1)
$AC = AO \cdot (1 - f\_v) + AO \cdot f\_v \cdot n\_am$ (2)
$NR = AC / t\_mr$ (3)
$RSA = F(NR, r\_f, m\_r)$ (4)

Conjectures
$\partial F/\partial NR > 0, \quad \partial F/\partial r\_f > 0, \quad \partial F/\partial m\_r > 0$ (5)

Waste Composition
$RSA = \Sigma\, AT\_i \quad (i=1 \text{ to } n)$ (6)

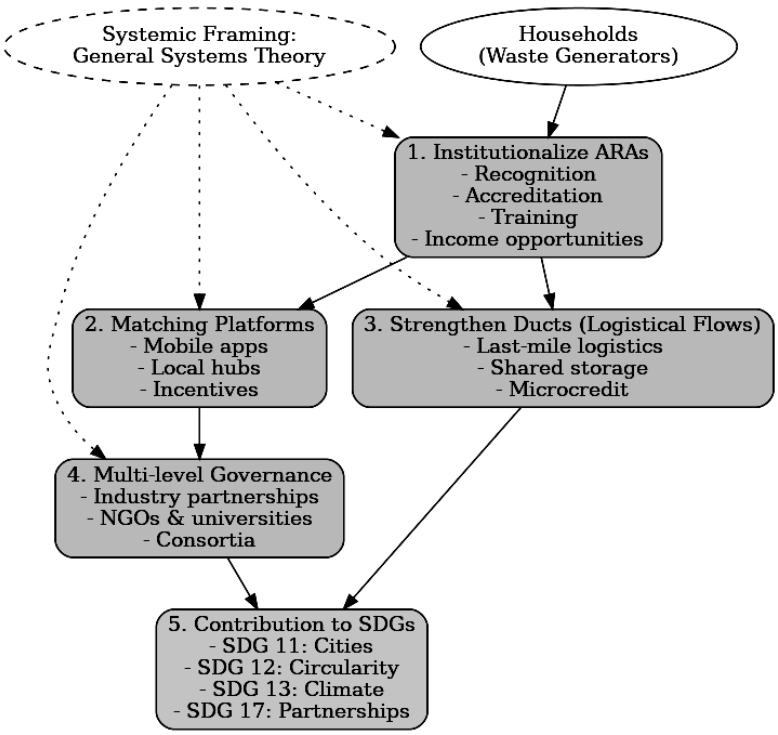
The temporal and compositional variability of AT_i across households highlights the complexity of local waste generation patterns. This complexity necessitates local management mechanisms, such as ARAs, to ensure material reuse and recycling. Such actors function as systemic nodes, enabling additional income opportunities and enhancing the resilience of the solid waste governance system.

5. RESULTS OBTAINED

Taken together, these premises and the mathematical model frame household solid waste recycling as a complex adaptive system consistent with the principles of General Systems Theory (GST). Localized micro-processes (P1, P2, P6) interact dynamically with broader systemic "arteries" (P3, P4), requiring coordination mechanisms that reduce friction and ensure continuity of material flows. By focusing exclusively on the household sphere (P5), the model isolates the most variable and socially embedded components of the waste stream, highlighting the importance of adaptive governance strategies.

Within this systemic perspective, Active Recycling Agents (ARAs) emerge as critical nodes capable of linking micro-level practices with macro-level infrastructures. Their institutionalization directly advances the 2030 Agenda, particularly by promoting responsible consumption and production (SDG 12), fostering sustainable cities and communities (SDG 11), contributing to climate action through waste reduction and lower emissions (SDG 13), and enabling partnerships for the goals (SDG 17). Thus, ARAs strengthen resilience, inclusiveness, and efficiency in Brazil's transition toward a circular economy. Moreover, our model displays Active Recycling Agents (ARAs) as systemic nodes linking households to governance structures, strengthening circular economy practices, and contributing to SDGs 11, 12, 13, and 17, as shown in Figure 2.

Figure 2 - Policy implications of integrating Active Recycling Agents (ARAs) into Brazil's solid-waste governance.



Source: authors.

The graphical model highlights households as the primary source of waste, with ARAs functioning as systemic nodes that link local practices to broader governance "arteries." The mechanisms include institutionalization, matching platforms, strengthening ducts (logistical flows), and multi-level governance, all framed by General Systems Theory (GST). Together, these interventions contribute to the achievement of SDG 11 (sustainable cities), SDG 12 (responsible consumption and circularity), SDG 13 (climate action), and SDG 17 (partnerships for the goals).

6 TECHNOLOGICAL-SOCIAL CONTRIBUTION

Padilha and Trujillo (2018), in their study Waste disposal and households' heterogeneity: Identifying factors shaping attitudes towards source-separated recycling in Bogotá, Colombia, demonstrated that both Brazil and Colombia face structural weaknesses in waste governance and maintain a strong reliance on the informal sector. Nonetheless, while Colombia's system remains heavily landfill-dependent and marked by higher per capita waste generation, Brazil has developed more comprehensive national policy instruments through the PNRS, although their implementation and effectiveness are still limited.

In this scenario, Active Recycling Agents (ARAs) have emerged as innovations in governance that integrate formal and informal systems. Their insertion into governance networks is both a technological solution and social strategy. ARAs function as collaborative nodes aligned with SDG 17, bridging household-level waste separation practices with macro-level policy frameworks. This ability to articulate micro and macro dynamics exemplifies the systemic interdependence highlighted by General Systems Theory (GST), which this study embeds into Brazilian waste governance as a novel framework.

The institutionalization of ARAs—through accreditation, cooperative arrangements, and digital matching platforms—has the potential to strengthen the resilience of recycling systems, reduce landfill dependency, and enhance inclusiveness in environmental governance. It also responds to Vieira's (2018) call to integrate social inequality into waste governance, recognizing that unequal realities demand differentiated solutions. Moreover, it extends Silva's (2019) insights into embryonic circular economy (CE) practices by proposing a systemic model in which ARAs operate as formalized policy instruments.

To accelerate Brazil's transition to a circular economy and the 2030 Agenda, this study proposes three complementary mechanisms: (1) creation of digital matching platforms to synchronize waste disposal and collection in real time; (2) investments in last-mile logistics, such as microcredit for vehicles or provision of shared storage facilities, to expand ARAs' operational capacity; and (3) Incorporation of ARAs into local and regional governance networks, enabling their participation in decision-making processes and ensuring that policies reflect community realities.

Ultimately, ARAs contribute directly to SDG 12 (responsible consumption and production), SDG 11 (sustainable cities and communities), SDG 13 (climate action), and SDG 17 (partnerships for goals). Their recognition as formal actors supported by municipalities and national programs represents a strategic pathway to operationalize the PNRS, bridge systemic gaps, and transform recycling into a more resilient, inclusive, and sustainable network. By advancing environmental objectives while promoting social equity and economic opportunity, ARAs have become indispensable agents in Brazil's circular economy transition to achieve the PNRS goals.

REFERENCES

ABRELPE. (2022). Panorama dos resíduos sólidos no Brasil 2022. Associação Brasileira de Empresas de Limpeza Pública e Resíduos Especiais. https://abrelpe.org.br
Bertalanffy, L. von. (1968). General system theory: Foundations, development, applications. New York: George Braziller.
Brasil. (2010). *Lei nº 12.305, de 2 de agosto de 2010. Institui a Política Nacional de Resíduos Sólidos; altera a Lei nº 9.605, de 12 de fevereiro de 1998; e dá outras providências.* Diário Oficial da União, Brasília, DF, 3 ago. 2010. http://www.planalto.gov.br/ccivil_03/_ato2007-2010/2010/lei/l12305.htm
Brasil. (2020, 15 de julho). Lei nº 14.026, de 15 de julho de 2020: Atualiza o marco legal do saneamento básico e altera a Lei nº 11.445/2007 e outras leis. Diário Oficial da União, 16 jul.
Calderoni, S. (2003). Os bilhões perdidos no lixo. Humanitas.
Checkland, P. (1999). Systems thinking, systems practice. Chichester: Wiley.
De Paula, F.; Lima, A.; Alves De Souza, M. (2016). Bem Público e Interesses Privados no Tratamento do Lixo Urbano: O Caso da Parceria Público-Privada dos Resíduos Sólidos em Minas Gerais. Em: *Catadores de Materiais Recicláveis: um encontro nacional*. Rio de Janeiro: IPEA, 337–357.
Ferreira, E. M. (2024). Waste pickers and their inclusion in Brazilian public environmental decisions: an analysis of 10 years of policy development. *Interações*, *25*(4).
Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. Journal of Cleaner Production, 114, 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007
Hollnagel, H. C., & Araújo, L. J. S. (2023, novembro 29–dezembro 1). A new model for fostering SDG 12 in Brazil: Active Recycling Agent – AAR can intensify the circular economy and boost waste collectors' income [Artigo completo]. XXV Encontro Internacional sobre Gestão Empresarial e Meio Ambiente (ENGEMA), São Paulo, Brasil. https://engema.org.br/25/wp-content/uploads/sites/15/2023/05/Premiacao-ENGEMA-2023-site.pdf
Hollnagel, H., Araújo, L. J. S., & Bueno, R. L. P. (2024, December 3–6). Environmental governance in Brazil: Synergies between active recycling agent (AARs) and small construction and demolition waste (CDW) generators to address SDGs. *In:* XXVI ENGEMA – Encontro Internacional sobre Gestão Empresarial e Meio Ambiente, Universidade de São Paulo, São Paulo, Brazil.
Jacobi, P. R., & Besen, G. R. (2011). Gestão de resíduos sólidos em São Paulo: Desafios da sustentabilidade. Estudos Avançados, 25(71), 135–158. https://doi.org/10.1590/S0103-40142011000200010
Ministério do Meio Ambiente. (2016). Plano Nacional de Resíduos Sólidos (PNRS). Brasília: MMA. Retrieved from https://www.gov.br/mma
Padilla, A. J., & Trujillo, J. C. (2018). Waste disposal and households' heterogeneity. Identifying factors shaping attitudes towards source-separated recycling in Bogotá, Colombia. Waste management, 74, 16-33.
Pisano, V., Demajorovic, J., & Besen, G. R.. (2022). The Brazilian National Solid Waste Policy: perspectives of the waste pickers' cooperative networks. *Ambiente & Sociedade*, *25*, e01511. https://doi.org/10.1590/1809-4422asoc20210151r1FT
Ribeiro, H., & Besen, G. R. (2011). Panorama da coleta seletiva no Brasil: Desafios e perspectivas a partir de três estudos de caso. InterfacEHS, 6(1), 1–21. http://www.interfacehs.sp.senac.br
Rittel, H. W. J., & Webber, M. M. (1973). Dilemmas in a general theory of planning. Policy Sciences, 4(2), 155–169. https://doi.org/10.1007/BF01405730
Seixas, C. S., Prado, D. S., Joly, C. A., May, P. H., Neves, E. M. S. C., & Teixeira, L. R. (2020). Environmental Governance in Brazil: towards the Sustainable Development Goals (SDGs)? *Cadernos de Gestao Publica e Cidadania*, *25*(81), 1-21.
Silva, F. C., Shibao, F. Y., Kruglianskas, I., Barbieri, J. C., & Sinisgalli, P. A. A. (2019). Circular economy: analysis of the implementation of practices in the Brazilian network. Revista de Gestão, 26(1), 39-60.
Skyttner, L. (2005). General systems theory: Problems, perspectives, practice (2nd ed.). Singapore: World Scientific Publishing. https://doi.org/10.1142/5552
Vieira, V. H. A. D. M., & Matheus, D. R. (2018). The impact of socioeconomic factors on municipal solid waste generation in São Paulo, Brazil. Waste Management & Research, 36(1), 79-85.