

Rate and direction of circular patents in the plastic industry: The trade-off between reducing and recycling innovations

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Context: Plastics

- Between 2000 and 2019, global plastic waste generation more than doubled, reaching 353 million tonnes [[18](#)].
- The fate of plastic waste highlights the low circularity of the plastics value chain:
 - Only 9% was recycled;
 - 19% was incinerated;
 - 50% ended up in controlled landfills;
 - 22% escaped formal waste management systems.
- The circular economy, based on the 4R model — Reduce, Reuse, Recycle, and Recover — is emerging as a key paradigm for transforming the plastics sector [[13](#), [12](#), [14](#)].

Context: Circular economy and waste hierarchy

Circular economy strategies

- **R1 Reduction:** prevention, material efficiency, substitution, eco-design.
- **R2 Reuse:** extending product life and repeated use.
- **R3 Recycling:** sorting, mechanical or chemical reprocessing.
- **R4 Recovery:** energy recovery from residual waste.
- Circular strategies span different stages of the value chain, from upstream material reduction and product redesign to downstream sorting, recycling and recovery.
 - Process innovations (e.g., advanced recycling techniques) and product innovations (e.g., low-impact polymer materials) are essential to support a transition toward circularity in the plastics industry [4, 14].
- This makes plastics a useful setting to examine whether circular innovation follows a single technological paradigm or distinct trajectories.

Policy tension

- The waste hierarchy ranks prevention and reduction above recycling and recovery.
- In practice, many CE instruments also set recycling targets and support downstream infrastructures.
- This creates a key question: **do policies redirect innovation toward higher-order strategies**, or reinforce existing technological specialization?

Literature (1): circular economy, 4R hierarchy and measurement

- This aggregation is problematic because R-strategies involve different problem–solution spaces, technological requirements and positions along the plastics value chain.
- The measurement issue is therefore also a directionality issue: identifying circular patents is not enough; we need to **identify which circular trajectory is being developed.**

In plastics, EU circular-economy policies combine a normative waste hierarchy with instruments that often operate through downstream incentives, such as recycling targets, EPR schemes and packaging regulation.

The open question is whether these **policies redirect inventive activity toward higher-order strategies such as reduction**, or instead reinforce existing recycling-oriented capabilities.

Research gaps

- Patent data are widely used to study inventive activity and eco-innovation [[10](#), [1](#)] but, its use for identifying circular economy (CE) innovation remains underexplored.
- Circular innovations are a subset of eco-innovations specifically aimed at enabling the transition to a circular economy [[7](#)].
- However, circular innovations are difficult to identify with standard patent classifications: CE strategies are cross-cutting, sector-specific and not fully captured by CPC-Y02 classes.
- Existing patent-based approaches often aggregate CE innovation into one category, which obscures the hierarchy and heterogeneity of the 4R strategies.

Motivations: from the literature to the research question

- **Measurement gap.** Standard patent classifications do not fully capture plastic-related circular innovation, especially when circularity is embedded in product design, material substitution or downstream applications.
- **Conceptual gap.** Circular innovation is often treated as homogeneous, although the 4Rs correspond to hierarchically ordered and technologically distinct strategies.
- **Knowledge gap.** We do not know whether accumulated R1 and R3 knowledge stocks are complementary, transferable, or instead associated with a trade-off.
- **Policy gap.** We do not know whether CE policy milestones have promoted diversification toward higher-order strategies or reinforced downstream recycling specialization.

Filling the gaps

To recover the direction of circular innovation by distinguishing R1, R2, R3 and R4, rather than treating CE as a homogeneous technological domain.

To extend the knowledge-base approach by showing how prior experience in different types of CE innovation (**Reduction (R1)** or **Recycling (R3)**) enable or constrain future CE innovation paths in plastics.

Contribution

How does accumulated knowledge in reduction or recycling shape the rate and direction of circular innovation in the plastics industry?

- Construct a novel text-based measure of plastics-related circular patents filed at the EPO.
 - Identify and quantify plastic-related eco-innovations that serve a circular objective.
- Distinguish circular inventions across the 4R framework and identify **R1 reduction** and **R3 recycling** as the two dominant trajectories.
- Estimate whether prior trajectory-specific knowledge increases persistence within a trajectory or constrains diversification across trajectories.
 - Assess whether firms follow a path-dependent trajectory in their circular innovation strategy.
- Test whether CE policy milestones are associated with changes in the returns to reduction and recycling knowledge.

Patents identification

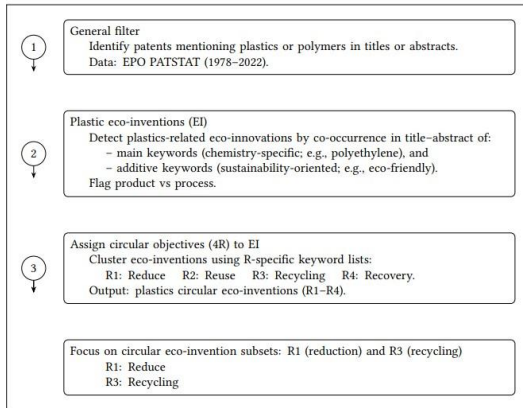
- The use of patents classifications
 - Cooperative Patent Classification (CPC)
 - International Patent Classification (IPC)
- **CPC Y02**: Technologies or applications for mitigation or adaptation against climate change. Selection of technologies which
 - Control, reduce or prevent anthropogenic emissions of GHG, in the framework of the Kyoto Protocol and the Paris Agreement
 - Allow adapting to the adverse effects of climate change.

Limitations

- Bias (over or under estimated)
 - Authority decides CPC code (ex: one patent, multiple authority, different CPC codes)
 - CPC revisions and reclassifications (2015, 2018, 2020) [3]
 - Quid of circular patents?
 - Y02P 20/143, Y02W 30/50, Y02W 30/62, and Y02W 90/10 (/300 CPC codes in Y02)
- We select patents based on a three-steps textual analysis performed on title and abstract of patents [8].

Textual analyses

Figure 1: Three-step textual analysis to identify circular plastics-related inventions



Note. Step 1 filters plastics-related patents. Step 2 detects plastic eco-inventions via co-occurrence of one main and one additive keyword in title-abstract (product vs process flagged). Step 3 assigns 4R circular objectives using R-specific keyword lists and reports counts for plastics circular eco-inventions (R1-R4). Step 4 narrows the analysis to R1 (reduction) and R3 (recycling).

Textual analyses

- 1 Plastic innovations: general filter,
 $N = 361,546$
- 2 Plastic eco-innovations,
 $N = 97,217$
- 3 EPO sample used in the estimations, $N = 30,744$
- 4 Circular patent–strategy assignments across the 4Rs,
 $N = 3,706$
 - Reduce, R1: $N = 1,749$
 - Re-use, R2: $N = 76$
 - Recycling, R3: $N = 1,301$
 - Recovery, R4: $N = 580$

Table 1: Keywords used for textual analysis of plastic eco-innovations.

Plastic eco-innovations	
Main Keywords	Additive Keywords
Bio(-)based Polyester Epoxy resin Recycling	Degradability, waste reduction Natural fiber composite Non-toxic, environmental Depolymerisation
Circular plastic eco-innovation	
R	Keywords
R1	Reduce, reducing, reduction
R2	Reuse(d), reusing
R3	Recycle(d, ing), reform(ed, ing)
R4	Recovery, energy recovery

Note: the 4R counts are patent–strategy assignments, not mutually exclusive patent counts; unique circular patents in the estimation sample

Figure 1: Dynamics of innovations in plastics.

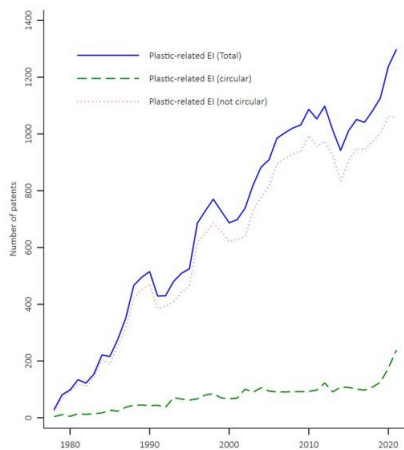
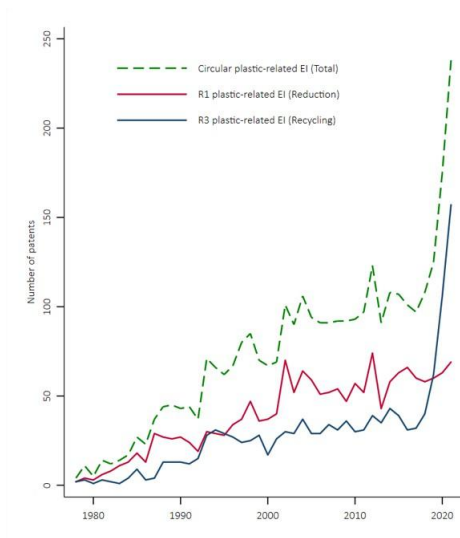


Figure 2: Dynamics of circular innovations in plastics.



Econometric model

We estimate how previously accumulated technological knowledge shapes the direction of subsequent circular inventive activity.

$$\text{Prob}(R_{\text{Patents}} = 1) = \beta_0 + \beta_1 R1_{\text{stock}} + \beta_2 R3_{\text{stock}} + \beta_3 \cdot \text{HighExperience} + \beta_4 \cdot \text{Controls} + \varepsilon \quad (1)$$

Variable name	Description
Dependent variables	
R_{Patents}	Alternatively, R1 and R3 . Dummy = 1 if the patent is identified as R1 or R3 , 0 otherwise.
Independent variables	
$R1_{\text{stock}}$	Firms' experience (knowledge) in R1 (Reduction) circular patents.
$R3_{\text{stock}}$	Firms' experience (knowledge) in R3 (Recycling) circular patents.
HighExperience	Dummy = 1 if firm's cumulative number of patents before the focal one is above median (192).
Controls	Other control variables included in the regression: number of inventors, type of applicant, CPC classes, time trends and country dummies.

Baseline results: direction of inventive search

- The estimates show two robust patterns:
 - **within-trajectory persistence;**
 - **negative cross-trajectory effects.**
- Prior recycling knowledge increases R3 patenting and reduces R1 patenting.
- Prior reduction knowledge increases R1 patenting and reduces R3 patenting.
- Effects for applicant type are relative to firms.

Table 2: Summary of baseline effects

Variable	R1	R3
R1 stock	+	-
R3 stock	-	+
High experience	-	-
University	-	NS
Individual	NS	+
Other applicant type	NS	+

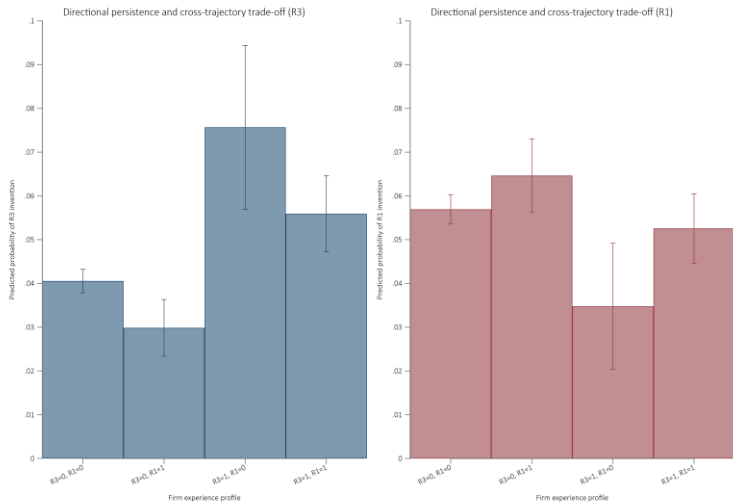
Baseline logit AMEs and LPM estimates, N = 30,744. Knowledge stocks are binary indicators equal to one after at least two prior patents in the corresponding trajectory.

Baseline results: direction of inventive search

- **Path dependence.** Applicants with established prior knowledge in R1 or R3 are more likely to continue inventing in the same technological direction.
- **Technological lock-in and trade-off.** Accumulated knowledge in one trajectory reduces the probability of inventing in the alternative trajectory.
- **Asymmetry.** Recycling knowledge displays stronger cumulative reinforcement than reduction knowledge. This is consistent with recycling being a more delimited downstream technological domain, while reduction is broader and more technologically diffuse.
- **No unified CE knowledge base.** Circular inventions in plastics are organized around distinct and only partially compatible trajectories rather than around a single integrated technological paradigm.
- **Applicants diversity and sectoral lock-in** *Individuals* and *other types* of applicants (e.g., collaborations) are more likely than firms to patent in R3. R1 innovations remain mostly patented by **firms**.
 - Highly experienced firms are **less likely** to innovate in circular technologies.

Heterogeneity

Figure 4: Predicted probabilities of recycling and reduction invention across knowledge stock profiles



CE Policy

Table 3: Post-policy shifts in returns to circular technological knowledge

	DV: R3 invention			DV: R1 invention		
	Post-2015	Post-2019	Post-2020	Post-2015	Post-2019	Post-2020
R3 stock	0.016***	0.011***	0.010***	-0.013**	-0.014***	-0.013***
R3 stock × Post-policy	0.014*	0.061***	0.088***	-0.000	0.005	0.002
R1 stock	-0.012***	-0.010***	-0.010***	0.012**	0.012***	0.011***
R1 stock × Post-policy	-0.005	-0.027**	-0.033**	-0.005	-0.014	-0.012
Δ Persistence	0.014*	0.061***	0.088***	-0.005	-0.014	-0.012
Δ Trade-off	-0.005	-0.027**	-0.033**	-0.000	0.005	0.002
Observations	30,744	30,744	30,744	30,744	30,744	30,744
Country dummies	Yes	Yes	Yes	Yes	Yes	Yes
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes

- Persistence measures whether policy increases the returns to knowledge accumulated within the same trajectory.
- After 2019 and 2020, returns to R3 knowledge increase strongly for R3 inventions (+6.1 pp; +8.8 pp).
- No comparable increase appears for R1, while the cross-trajectory effect of R1 knowledge on R3 inventions becomes more negative (-2.7 pp; -3.3 pp).
- This suggests that policy sequencing reinforces downstream recycling specialization.

Conclusion

Implications

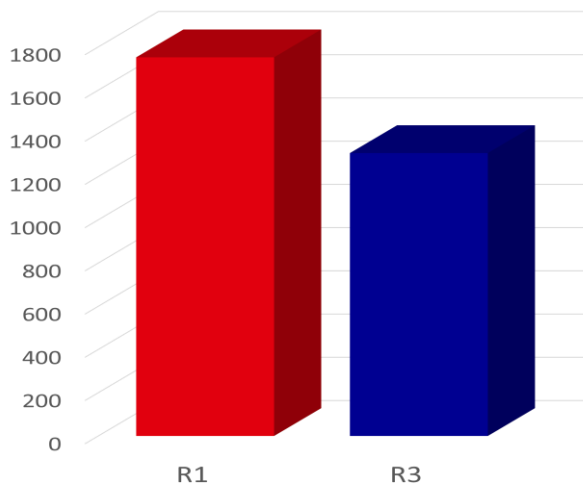
- A firm's patenting experience shapes its future innovation choices: path-dependent inventive pattern for circular innovations.
- Trade-off: absence of self-reinforcing dynamics between these two types of technologies.
- Heterogeneity in innovation capabilities. Collaborations between different types of actors generate knowledge spillovers.

Discussion

- These results suggest policy implications, including the design of innovation and circular policies aiming to foster the transition towards a circular model.
 - R&D subsidies towards breakthrough Reduction (R1) technologies.
 - Support diverse applicant types and new entrants.
 - Foster collaboration across public and private sectors.

Appendix

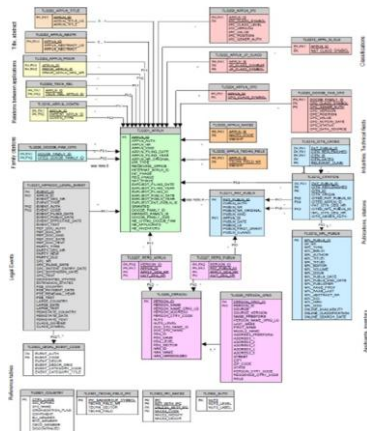
Figure 5: Reduction (R1) and Recycling (R3) patents.



Data

- PATSTAT, v. Spring 2024
- European Patent Office (EPO)
- Files TLS 201, 202, 203

Figure 6: PATSTAT dataset.



- Y02A Technologies for adaptation to climate change
 - Technologies that allow adapting to the adverse effects of climate change in human and economic activities
- Y02B Climate change mitigation technologies related to buildings
- Y02C Capture, storage, sequestration or disposal of greenhouse gases (GHG)
- Y02D Climate change mitigation technologies in information and communication technologies (ICT) aiming at the reduction of their own energy use
 - ICT whose purpose is to minimize the use of energy during the operation of the involved ICT equipment
 - /= The use of an ICT technology supporting energy-efficient operation of a piece of equipment, nor the reuse or recycling of ICT equipment
- Y02E Reduction of greenhouse gas (GHG) emissions, related to energy generation, transmission or distribution
- Y02P Climate change mitigation technologies in the production or processing of goods
 - Climate change mitigation technologies in any kind of industrial processing or production activity, including the agroalimentary industry, agriculture and fishing
- Y02T Climate change mitigation technologies related to transportation
- Y02W Climate change mitigation technologies related to wastewater treatment or waste management

CPC Classes

Table 4: The Nine CPC Classes

CPC	Description
A	Human necessities
B	Performing operations; transporting
C	Chemistry; metallurgy
D	Textiles; paper
E	Fixed constructions
F	Mechanical engineering; lighting; heating; weapons; blasting engines or pumps
G	Physics
H	Electricity
Y	General tagging of new technological developments; general tagging of cross-sectional technologies spanning over several sections of the IPC

[Back to presentation](#)

Patent selection

Figure 7: Examples

(54) Title of the Invention: **Method for producing low-cost fully biodegradable disposable straw**
 Abstract Title: **Method for producing low-cost fully biodegradable disposable straw**

(57) Biodegradable disposable straw production comprises pulverizing natural plant material to prepare a powder, pulverizing konjac gel, followed by swelling in water and stirring to obtain a swollen konjac gel. Water and Calcium hydroxide are added and stirred to produce a deacetylated konjac gel. Sodium hydroxide solution is added to a taro starch-cassava starch mixture and mixed, heated and filtered to obtain a taro starch-cassava starch crude product. Water is added to obtain a starch slurry, sodium sulphate added then stirred. The PH of the slurry is adjusted and crosslinker added. The starch slurry is subjected to ultrasonic and microwave treatment in a water bath and PH adjusted again. The slurry is washed with distilled water then dried in an oven and pulverised to obtain a crosslinked taro starch-cassava starch powder. The crosslinked taro starch-cassava starch powder, deacetylated konjac gel, a natural plant powder, a bio-based biodegradable plastic, a stabilizer and a nucleation agent are mixed by stirring to obtain a raw material mixture, which is heated, fed to a beverage straw manufacturing machine. This is followed by extrusion, cooling forming, traction and cutting to obtain a straw crude product. Quality inspection, disinfection and packaging also takes place.

(a) Example of relevant patent

(54) **ENVIRONMENTALLY FRIENDLY DISHWASHING POWDER FOR HAND DISHWASHING**

(57) Eco-friendly dishwashing powder for hand washing comprising a combination of dry mustard, baking soda and citric acid. It is 100% composed of natural food ingredients. It is perfect for washing any very oily kitchen utensil: be it metal, ceramic, glass, plastic or wood. It removes grease and odors even in cold water. It is an effective

and economical detergent. The water consumption is reduced. Absorbs grease instantly on any kitchen utensil, especially suitable for washing pans and trays, as they cannot be washed in the dishwasher. It perfectly washes grease from surfaces of any type of stove: gas, electric, induction and does not damage the surface.

(b) Example of irrelevant patent

Table 5: Main results

	Logit		OLS-LPM	
	(1) R3	(2) R1	(3) R3	(4) R1
knowledge base in R3	0.711*** (0.103)	-0.272*** (0.089)	0.025*** (0.004)	-0.013*** (0.005)
knowledge base in R1	-0.345*** (0.105)	0.171** (0.077)	-0.011*** (0.003)	0.009** (0.004)
High overall patenting experience	-0.325*** (0.082)	-0.150** (0.065)	-0.010*** (0.003)	-0.008** (0.003)
Inventor team size	0.005 (0.017)	-0.011 (0.014)	-0.000 (0.001)	-0.001 (0.001)
University applicant	0.102 (0.172)	-0.289* (0.154)	0.002 (0.007)	-0.015* (0.008)
Individual applicant	0.751*** (0.117)	0.078 (0.122)	0.038*** (0.006)	0.005 (0.007)
Other applicant type	0.703*** (0.096)	-0.094 (0.110)	0.044*** (0.005)	-0.004 (0.006)
Observations	30,744	30,744	30,744	30,744

Complementarity versus specialization

Table 6: Interaction effects between reduction and recycling knowledge bases

	Logit AME		OLS-LPM	
	R3	R1	R3	R1
Knowledge stock in R3	0.033*** (0.008)	-0.019*** (0.006)	0.038*** (0.010)	-0.019*** (0.007)
Knowledge stock in R1	-0.012*** (0.004)	0.009** (0.004)	-0.008*** (0.003)	0.007 (0.005)
R3 stock × R1 stock	-0.009 (0.011)	0.010 (0.009)	-0.018 (0.011)	0.007 (0.009)
Observations	30,744	30,744	30,744	30,744
Country dummies	Yes	Yes	Yes	Yes
Period dummies	Yes	Yes	Yes	Yes

- Own-trajectory knowledge remains positive, while cross-trajectory effects remain negative.
- The interaction term is not significant: R1 and R3 knowledge stocks do not reinforce each other.
- This supports a specialization mechanism rather than an integrated circular knowledge base.

Robustness: alternative knowledge-stock thresholds

Table 7: Entry versus established trajectory-specific knowledge

	DV: R3 invention		DV: R1 invention	
	Entry threshold ≥ 1 prior patent	Established threshold ≥ 3 prior patents	Entry threshold ≥ 1 prior patent	Established threshold ≥ 3 prior patents
R3 stock	0.026*** (0.003)	0.036*** (0.005)	-0.006 (0.004)	-0.008 (0.005)
R1 stock	-0.014*** (0.003)	-0.016*** (0.003)	0.006 (0.004)	0.004 (0.005)
Δ Persistence	0.026	0.036	0.006	0.004
<i>p</i> -value	0.000	0.000	0.140	0.374
Δ Trade-off	-0.014	-0.016	-0.006	-0.008
<i>p</i> -value	0.000	0.000	0.126	0.115
Observations	30,744	30,744	30,744	30,744
Country dummies	Yes	Yes	Yes	Yes
Period dummies	Yes	Yes	Yes	Yes

- The baseline results are not driven by the threshold used to define knowledge stocks.
- For R3, persistence is positive and significant under both thresholds; the cross-effect of R1 remains negative.
- For R1, persistence remains weaker and statistically insignificant. The asymmetry is therefore mainly driven by recycling-oriented lock-in.

PEPR Recyclage, Recyclabilité, Réutilisation des matières – Axe Déchets Ménagers

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PEPR Recyclage, Recyclabilité, Réutilisation des matières – Axe Déchets Ménagers

Déchets ménagers

OBJECTIFS

Acquérir les connaissances pour améliorer le recyclage des déchets ménagers

- ✓ **Identifier les verrous à résoudre pour une stratégie de recyclage/réutilisation efficace**
 - Technique-technologie
 - Comportemental – sociétal
 - Politiques : Économique, législation, normalisation, ...

- ✓ **Proposer des technologies innovantes afin d'améliorer le recyclage et la recyclabilité des déchets**
 - Tris innovants
 - Préparation des déchets

- ✓ **Identifier les obstacles socio-économiques et réglementaires : compréhension de la dynamique/comportement des acteurs**
 - Enquêtes pour comprendre le comportement de chacun
 - Proposer un outil d'aide à la décision

- ✓ **Évaluer et optimiser les scénarios et les stratégies**
 - Modélisation systémique intégrant le processus-le comportement des chaînes d'approvisionnement- l'évaluation économique et environnementale
 - Modéliser les scénarii alternatifs