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Technology evolution in heterogeneous technological fields: A main path analysis of plastic recycling

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ABSTRACT

Driven by the ubiquity of plastic waste and its danger to environment and health, there have been increased efforts in the development of plastic recycling technologies. However, plastic recycling is a heterogeneous technological field which involves different application contexts, process stages, and technological approaches. In this paper, we study the structure of interrelated technological development of different recycling technologies. Utilizing patent citation data on more than 100,000 patents and focusing on textile applications, separation techniques, and biological recycling as example subdomains, we use patent-based main path analysis to delineate the co-evolution of technological trajectories. We report two main findings: First, comparative analysis of the three domains shows that differences in main path cohesion and homogeneity coincide with differences in development maturity and organizational concentration of patenting activity. Second, integrated analysis of the three domains shows a strong degree of historical dependence between textile recycling and separation techniques while biological recycling has so far mostly developed in its own niche.

1. Introduction

The plastic waste crisis has taken the center stage in many arenas of politics and policy: In March 2022, representatives of 175 states signed a resolution to end plastic pollution in the context of the United Nations Environment Assembly (United Nations, 2022). And since July 2021, many single use plastics are banned from distribution in the European single market (European Commission, 2021). And indeed, the situation is dire: Geyer et al. (2017) estimate that of more than 8,000 Mt of plastics produced since the 1950s, about 60% accumulate in landfills and the environment while less than 10% of plastic waste has been recycled, a rate which is even lower for specific market segments, such as fiber plastics.

Expectations are accordingly high for the field of plastic recycling to provide novel techniques that can yield higher recycling rates (Garcia and Robertson, 2017). However, plastic recycling is a good example for the complexity of innovation in heterogeneous technological fields: First, technological developments are often interrelated in that the usefulness or feasibility of one new technology hinges on the state of another, or on the compatibility with the technological status quo. Consequently, it is rarely enough for policy makers or innovation managers to monitor individual technology alternatives, but instead decision makers need to evaluate networks of interdependent technologies. Second, technological progress is path dependent (David, 1985; Dosi and Nelson, 2010): Innovation and technology adoption do not take place in a vacuum but are embedded into firm histories and existing knowledge bases and their success accordingly often depends on their compatibility with the status quo (Breschi et al., 2003; Makri et al., 2010).

In this context, the goal of this study is to capture patterns of historical dependence among the constituent subdomains of the field of plastic recycling that arise as a consequence of interrelated and path dependent development. Although there are many studies that focus on single science and technology domains, such as fuel cells (Ho et al., 2014; Verspagen, 2007), coronary disease treatments (Fontana et al., 2009; Mina et al., 2007), or CRISPR sequencing (Magee et al., 2018), more holistic studies focusing explicitly on the interplay of a diverse set of technologies are much rarer – a research gap which we aim to address here.

The analysis presented in this paper focuses on the interrelated technical evolution of three subdomains in the field of textile recycling which represent different challenges and approaches: textile recycling, separation techniques and use of enzymes for biological degradation of polymers. Textile recycling is highly relevant due to the rise of fast

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fashion and the accompanying rise in textile wastes, but also brings its own challenges (Bianchi et al., 2023). Separation techniques are a critical building block of more comprehensive recycling, e,.g., of composite materials, which makes them also highly relevant for textile and fiber recycling (Colombo et al., 2021). Finally, enzymatic recycling represents a recent and radically different approach to recycling building on biotechnology, which is potentially disruptive but for now is not yet widely applied (Carniel et al., 2021).

In our analysis, we utilize patent citation data and a variant of main path analysis to delineate the co-evolution of technological trajectories. Patent data provide a unique resource for tracing technological dependencies over long periods of time and at great technological detail. Main path analysis can make use of these data to find empirical approximations of technological trajectories, which can then be used for structural examination. While main path analysis is usually used to investigate the history of technology development within a single technology, we here use a more comparative and integrative approach that captures interdependencies between different technologies within a field, in line with the issues discussed above. While the approach we choose here is historical in nature and we accordingly do not attempt to make a forecast about the future trajectory of the field, we believe that more refined analysis of the patterns that emerge as technologies coevolve can provide building blocks for more predictive endeavors. In line with this, our contribution is twofold: First, we show the interrelated nature of technological development and the coevolution of technological trajectories based on an empirical case study of technological evolution in the field of plastic recycling. Second, we provide a simple methodological extension of existing main path analysis techniques to identify structural features of historical (in)dependence of technology development across multiple subdomains.

The paper proceeds as follows: Section 2 gives a brief overview of the current state of plastic recycling technologies and its challenges. Section 3 discusses the literatures on technological change and technological trajectories. Section 4 then describes the data selection process and introduces the main path analysis method before section 5 presents the results of the empirical analysis. Section 6 discusses the findings and their implications for future research.

2. Plastic recycling: A brief overview

The technological field of plastics recycling broadly includes all processes that enable further utilization of discarded or residual plastic materials. The literature distinguishes four types of recycling: primary, secondary, tertiary and quaternary recycling (Hopewell et al., 2009; Lee and Liew, 2021).

Primary recycling, or closed-loop recycling, involves recovering an equivalent output, primarily from post-industrial waste with high purity. It is also pursued for some post-consumer waste, especially with deposit schemes ensuring selectivity. However, even with the ‘poster child’ of recycling, PET bottles, only about 17% are turned back into plastic bottles in Europe (eunomia, 2022), with downcycling, e.g., to polyester fibers, being the norm. Primary recycling relies on mechanical reprocessing, typically via extrusion, using heat and pressure to reshape polymer materials. While mechanical routes exist for common polymers like PET, HDPE, LDPE, and PP, they must ideally be treated separately due to differing susceptibilities to degradation (Schyns and Shaver, 2021). Recent studies also explore recycling more exotic polymers, such as polylactic acid, a biopolymer (Beltrán et al., 2019).

Secondary recycling involves mechanical processes that downgrade the original material, like turning high-quality PET from clear bottles into polyester fibers (Park and Kim, 2014; Tshifularo and Patnaik, 2020). It often includes preprocessing steps like separation, contaminant removal, and shredding to ensure purity (Ignatyev et al., 2014; N. Singh et al., 2017). Reducing the material degradation that commonly comes with recycling contaminated post-consumer wastes is one of the major research challenges in the field (Antonopoulos et al., 2021; Eriksen et al., 2019; Larrain et al., 2021; Soto et al., 2018). In this vein, recent research focuses on issues like composite material recycling (Colombo et al., 2021; Palme et al., 2017; Rocchetti et al., 2018), solvent-based (Ügdüler et al., 2020; Walker et al., 2020) and biotechnological separation (Jönsson et al., 2021; Navone et al., 2020), and avoiding composite materials altogether (Jabbari et al., 2016).

In contrast to primary and secondary recycling, tertiary recycling involves depolymerization into monomer components (Hopewell et al., 2009). Lee and Liew (2021) outline three tertiary recycling approaches: thermal degradation (pyrolysis), chemical degradation, and biological (enzymatic) degradation. Pyrolysis handles mixed waste streams but yields fuels unsuitable for plastic production, while chemical and biological methods are more selective but produce reusable components like ethylene glycol or terephthalic acid. While pyrolysis and some chemical methods are established, biological recycling is still in its infancy: Sparked by the discovery of plastic-degrading bacteria (Bornscheuer, 2016; Yoshida et al., 2016), current research focuses on identifying the most effective bacterial strains and enzymes (Tournier et al., 2020), with some promising industrial applications in sight (DeFrancesco, 2020).

Finally, quaternary recycling refers to energy recovery through incineration of waste. While plastics have high energy density in principle, waste incineration has higher CO_2 emissions (Jeswani et al., 2021; Wollny et al., 2001) and lower energy recovery rates (Overcash et al., 2020) compared to other recycling approaches. It is generally only preferrable as an option when material recovery is not feasible (Al-Salem et al., 2009).

This brief overview already illustrates the technological complexity of recycling plastic materials: There is no one-size-fits-all approach but instead the efficacy of each method depends greatly on characteristics of the input material, such as polymer structure, waste composition, degree of contamination as well as on application context and the desired outputs. There is also great potential for interdependencies across technical subdomains: The development of more effective separation techniques, for example, would increase the relative usefulness of material-specific recycling approaches and could spur development of recycling techniques for multi-component applications. In the context of this heterogeneous technological field, the aim of this paper is to explore differences and interdependencies in the development pathways of technology subdomains relating to specific application contexts, process stages, and approaches.

2.1. Example technologies for empirical analysis

In our patent-based empirical analysis of the interdependence between technological developments, we limit our attention to three technical domains in the larger field of plastic recycling: First, textile recycling as a large but specific use case: Textile recycling has increasingly received public attention over the rise of fast fashion but poses unique challenges compared to the more mainstream issue of recycling plastic packaging and so far only shows low recycling rates (Bianchi et al., 2023; Geyer et al., 2017). The textile industry not only covers large consumer markets, such as apparel and footwear, but also comprises a broad range of industrial and household applications, such as carpeting, the automotive sector, or geotextiles. As such, synthetic textiles by themselves encompass a variety of materials and properties that are utilized in different contexts, from polylactic acid nonwovens for hygiene products to nylon fabrics for apparel or polyester fibers for artificial turf. For some of the most common textile materials, such as polyester, nylon, or cotton, recycling routes exist in principle (Harmsen et al., 2021).

Second, as in the case of packaging, a main challenge in recycling textiles and fiber materials is the use of composite materials such as polyester-cotton blends (Colombo et al., 2021; Palme et al., 2017), which are pervasive across the industry. Given this pervasiveness combined with the material selectivity of most existing recycling techniques, separation is a central preprocessing step across applications. Many different separation techniques exist, such as density (Gent et al., 2009) or flotation separation (Wang et al., 2015), or solvent-based approaches (Zhao et al., 2018). While the former are useful for separating materials of different density or with different surface properties in mixed waste streams, the latter is used to separate more complex polymer composites and promises to yield results of higher purity. Due to their role as a process stage of cross-sectional relevance, we investigate separation techniques as a second subdomain in the field of plastic recycling.

And third, we investigate biological or enzymatic recycling techniques, as a promising new avenue which has only recently emerged but which caters to many demands for sustainable new technologies and is regarded as a potential building block for a circular plastics economy (Zimmermann, 2020). While recycling based on enzymatic depolymerization has seen rapid improvements, it still faces challenges for large-scale industrial application, e.g., due to longer reaction times compared to chemical recycling (Carniel et al., 2021). Despite these challenges, recent life-cycle assessment studies have been favorable and predict cost-competitiveness as well as significant reductions in environmental impacts and greenhouse gas emissions compared to production of virgin plastics (A. Singh et al., 2021). While most applications of biological recycling have so far investigated recycling of PET, the technique could realize environmental benefits especially in combination with biodegradable plastics (Roohi et al., 2017). We include enzymatic recycling in our selection of technological subdomains because it differs from more conventional approaches in terms of the underlying knowledge base and necessary technological preconditions: Enzymatic recycling is based on biotechnology as compared to mechanical engineering and classical polymer chemistry, which form the basis for mechanical and chemical recycling.

We expect these three technological subdomains to exhibit different degrees of interrelatedness in their history of development: Due to their frequent reliance on composite materials, techniques for the recycling of textile and fiber applications can be expected to co-evolve with separation techniques. Enzymatic recycling, in contrast, can be expected to follow a largely separate development path due to its origins in a distinct knowledge base. The goal of this paper is to explore to what degree such technological coevolution or disconnect is identifiable through the structure of evolving patent citation networks.

3. Data and methods

3.1. Patent data and selection strategy

Patent data have been utilized as a technology or innovation indicator for many years due to their unparalleled ability to provide both detailed insights into specific technologies and high coverage with respect to technological fields, historical development, and geography (Bekkers and Martinelli, 2012; Hall et al., 2005; Jaffe et al., 1993). However, patent-based indicators are also not without issues, especially when the ultimate goal is to evaluate economic performance: While many patents are of little impact or worth, some protect immensely lucrative business models, and telling which one is which is not trivial (Griliches, 1990). This shortcoming is often argued to be less of an issue when the focus is not on the value of individual patents but on the larger structure and development of a technology field (Verspagen, 2007), an approach which is also chosen here.

The first step in any patent analysis is the selection of an appropriate subset of patents to study. In the wake of the application process, patents are classified by expert examiners according to standardized technology classification systems, such as the Cooperative Patent Classification (CPC) collaboratively implemented by the European Patent Office (EPO) and the United States Patent and Trademark Office (USPTO). Such classification systems often provide a good starting point for topical patent searches. For tracing technologies in plastic recycling, we here select patents classified in either the maingroups B29B17 (titled ‘Recovery of plastics or other constituents of waste material containing plastics’), C08J11 (titled ‘Recovery or working-up of waste materials’; this maingroup contains subgroups on recovery of waste solvents and polymers), and the subgroup Y02W30/62 (titled ‘plastics recycling; rubber recycling’). We then download all patent applications classified with at least one of the above labels from the open data platform Lens (2021) as of October 2022, for a total of 116,021 applications. As protection for a single invention is often sought in multiple jurisdictions, there can be multiple applications per invention, which form what is called a patent family. In our dataset, applications are grouped into a total of 61,321 families, for an average family size of 1.9. In the following, the terms ‘patent’ and ‘family’ will be used interchangeably.

3.2. Patent citation networks

A key feature of patent data is the inclusion of citations to related prior patents (and non-patent literature) during the examination of an application’s novelty. This enables the compilation of patent citation networks and the tracing of technological development ‘chains’. Because in some jurisdictions (such as the EPO) citations to related technologies are collected by the examiner and not by the applicant (as is the case in the US), a citation does not necessarily allow for the interpretation that the cited patent was a direct reference to the invention covered by the citing patent. Nevertheless, a citation implies that the earlier technology is in some way relevant for or related to the later technology, which enables the tracing of path dependencies in technological development. We here extract the (reverse) citation network at the family level by creating an edge from family f_1 to family f_2 if at least one application from the latter cites an application from the former and if the earliest filing date of f_2 is after that of f_1. This second step is to prevent citations ‘into the future’, which can occur as a consequence of the time lag between applications in a family and the resulting potential for bidirectional overlap between families. Such citations would create cycles in the citation network and thus destroy its property as a directed acyclic graph (DAG), which is required for methods such as main path analysis. Applied to our selection of families, the procedure then yields a citation network with a total of 57,956 family-to-family edges. Beyond citations *among* the selected patents, there is also the possibility of citations to patents outside of the selection. Among the 200,548 total citations issued by the applications in the set, 84,228, or around 42%, are to other applications included in the selection, i.e., those applications having one of the specified classification labels. We here restrict our attention to the network of citations among patents within the field of plastic recycling.

3.3. Main path analysis

To empirically explore structural features in the technological coevolution of plastic recycling technologies, we here employ a variant of main path analysis, a bibliometric method first proposed by Hummon and Doreian (1989) in a study on the development of DNA theory. The principal idea behind the method is, as the name implies, the extraction of the most important citation path(s) from a given citation network. As such, we regard main path analysis first and foremost as a tool for complexity reduction as it provides a filtered view into a potentially large and complex network. While there are many variants of the method (for a recent overview, see Liu et al., 2019), most variants involve two steps: First, the computation of some kind of traversal weight for either nodes or edges, and second, the traversal of the network along the highest weight paths given one or more starting positions, yielding the actual main path(s). For traversal weights, we here employ the Search Path Count (SPC) method, for which an efficient algorithm was given by Batagelj (2003), which we implemented in an open source software package for the Julia programming language (MainPaths.jl). SPC implements a concept of ‘flow’ through the citation network, where edges (or nodes) that lie on many of the paths connecting source nodes (i.e., nodes without any cited predecessors) to sink nodes (i.e. nodes without any citing successors) will receive high traversal weights. While there are other methods to obtain traversal weights, such as SPLC (Hummon and Doreian, 1989) or genetic knowledge persistence (Martinelli and Nomaler, 2014), SPC is one of the conceptually most simple, one of the most widely used, and one of the computationally most scalable procedures, making it a good default for the case at hand (Barbieri et al., 2016; Batagelj, 2003; Batagelj et al., 2017; Kim and Shin, 2018; Liu et al., 2019).

Step two in the extraction of main paths from a citation network first involves the selection of a set of start patents, at which traversal along the highest-weight edges is to commence. A typical choice for start patents that does not account for other considerations than the structure of the network is the set of all source nodes, i.e. all nodes that have no citations to earlier patents. Fig. 1 contains an example of main path analysis using SPC weights and arbitrarily selected start points. Instead of an agnostic choice of start patents, we here rely on a three-step procedure to capture main paths for different topics in plastic recycling: First, we select a CPC subgroup label representing a target technology as a classification requirement for a start patent. To identify patents within the technological domains of textile recycling, separation, and enzymatic recycling selected for analysis, we filter the subset of recycling patents by CPC section label 'D', class label 'B03', and subgroup label 'C08J11/10', respectively. Second, we specify a time window from which a start patent may be selected. We here limit the start window to patents filed before 2020 because for very recent patents forward citations become unreliable as an indicator of impact (see next step). To preserve a focus on technologies that might still carry some relevance today, we also limit start patents to those filed after 1995 (20 years is the maximum lifetime of a patent, which we extend by 5 years to capture the growth period in the late 1990s, occurring especially in Japan). Third, we pick the $k = 20$ patents from the selection yielded by step 1 and 2 which score highest in terms of year-normalized forward citations and where k is chosen to yield main path networks with manageable complexity. Year-normalization is performed to counteract recency-biases induced by the fact that older patents had more time to accrue citations. Given the set of start patents with the specified requirements, a forward and backward traversal of the citation networks is performed, where the neighbor chosen in each traversal step is the one with the highest traversal weights. Note that while the main path for a given topic is started at patents belonging to that topic, it is allowed to move to any family in the full sample as part of the following traversal to allow for overlaps in the topical main paths.

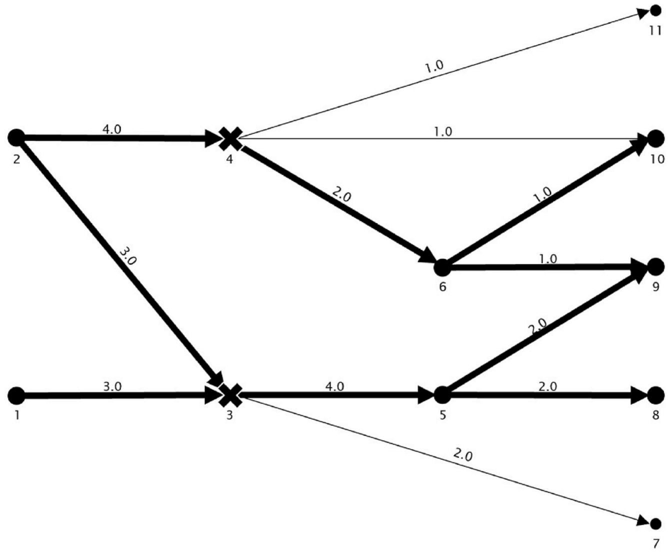

Fig. 1. Example of main path extraction. The thick paths represent the forward-backward main path originating at the start points represented by crosses. Edge weights are SPC traversal weights and count the total number of paths from source to sink nodes that lead through an edge.

4. Results

4.1. Patenting boom in plastics recycling

Looking at the overall trend of newly published patent applications over the last 30 years, two growth periods stand out: the first in the 1990s and early 2000s, and the second starting around 2010 and accelerating recently, with a 10-year period of stagnating growth in between (Fig. 2A). Differentiating between the jurisdictions in which an application was filed (Fig. 2B), we can see that the first growth period was especially driven by Japanese patent applications, while the second growth period is due to an explosion of applications in China. The latter trend is generally observable across many technology areas and is at least partly explainable by a government-driven push to create an internationally competitive Chinese patenting system, which drove up domestic application numbers but also came with a drop in patent quality (Prud'homme, 2015; Sun et al., 2021). The strong growth of recycling patent applications in Japan during the 1990s and early 2000s coincides with a policy push in the form of a waste management reform, as implemented in the Containers and Packaging Recycling Act enacted in 1995 or the Home Appliances Recycling Act enacted in 1998 (Japanese Ministry of the Environment, 2014). In comparison, patenting in the US and Europe for the field of recycling appears to be on a trajectory of slow growth, with some slight acceleration over the last 10 years. Comparing recycling to patenting trends in all technologies, it seems that recycling has received disproportionate attention: The number of published applications in recycling has increased by a factor of 14.9 from 1990 to 2020, compared to a factor of 5.3 across all technologies. Overall growth is still larger for recycling compared to all technologies when taking Japan and China out of the equation, albeit at a much lower multiplier of about 6.4.

4.2. Structural heterogeneity across technical domains

We next investigate the three example topics of textile recycling, separation technologies and enzymatic recycling in terms of (a) their historical trend of patent activity, (b) the concentration of patenting activity on certain organizations (i.e., the patent applicants), (c) the concentration of patenting activity on certain markets (i.e. the jurisdiction where the patent has been filed), and (d) the structure of the respective main path network extracted from the overall network of patent citations (Table 1). In our assessment of these characteristics, we furthermore distinguish three sets of patents: First, all families within the topic (i.e., with the respective CPC classes). Second, the 20 high-impact start patents at which the main path traversal is initialized. Third, the patents that make up the topic's main path. Based on these, we compare aggregate statistics on organizational and geographic composition and network structure among the topics and against the full sample of recycling patents (Table 1). Fig. 3 contains a visual representation of the main path networks of the three topics.

First, the topics vary strongly in terms of size and maturity: While close to 1,500 patent families feature CPC classes associated with separation techniques, only 234 patent families concern enzymatic recycling techniques, with textiles somewhere in the middle. Furthermore, most applications on enzymatic recycling are very recent, with a median earliest publication date of 2018. This reflects the fact that major breakthroughs have only recently occurred, such as the discovery of the PET-degrading bacteria strain *Ideonella sakaiensis* found at a Japanese recycling plant (Yoshida et al., 2016). This serendipitous discovery has been key for enabling biological plastic recycling as a feasible approach and has spawned downstream research in genetic optimization of the involved enzymes (Tournier et al., 2020).

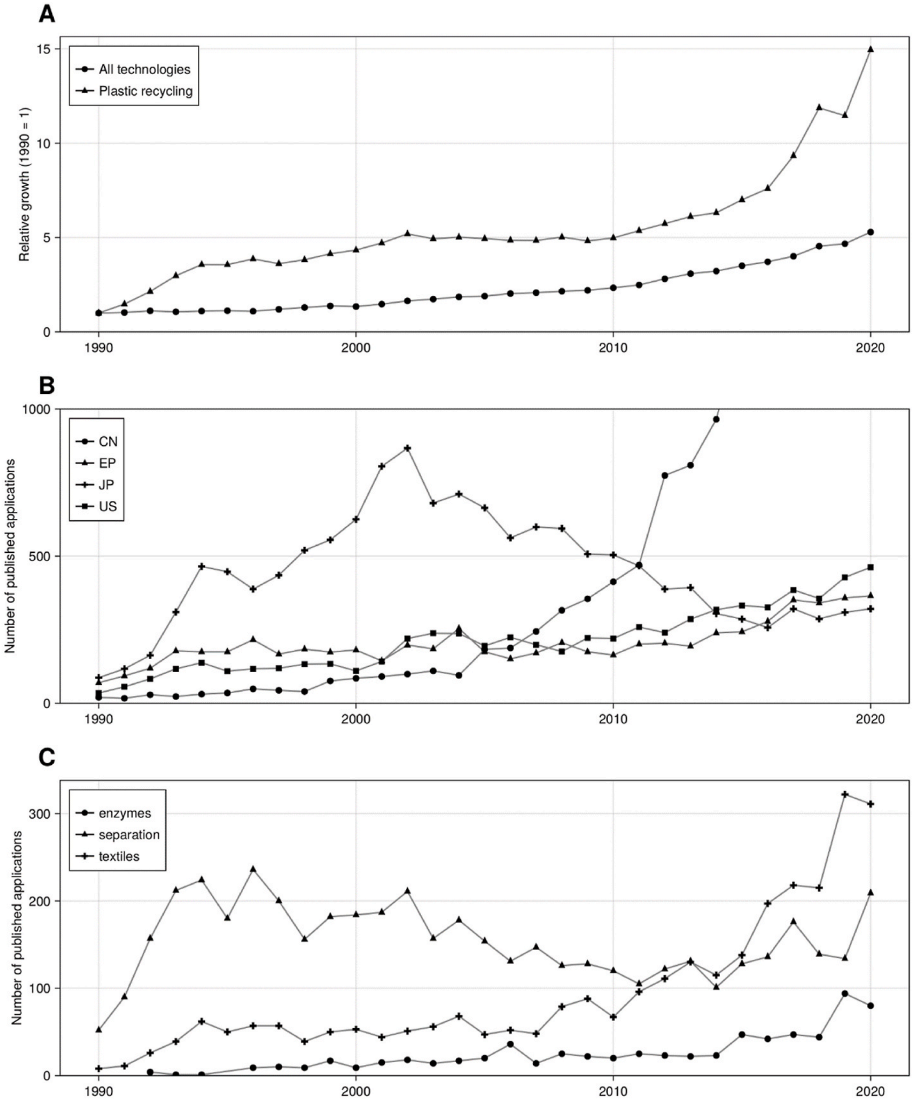

Fig. 2. Patenting trends in plastic recycling, 1990–2020. A: Overall trend of patenting in plastic recycling compared to all technologies. B: Decomposition of the plastic recycling trend by jurisdiction. C: Patenting activity for the three selected subdomains. Note: The y axis in Panel B is truncated for readability; The series for China extends to more than 4,000 published patents by 2020.

Separation technologies, on the other hand, had a peak in the 1990s, followed by a long period of stagnation, and have only recently experienced another push. For textile recycling, an initial period of slow to no growth has been superseded by a strong expansion of patenting activity over the last decade. Fig. 2C shows a summary of growth trends in the three domains. Second, the three topics vary strongly in their degree of organizational concentration: Table 1 gives values for the Herfindal-Hirschman Index (HHI) indicating the degree of concentration in the distribution of patent families across applicants (and jurisdictions). A value of 1 would indicate that a single organization holds all patents (the lower bound depends on the number of organizations). Again, enzymatic recycling stands out, with a comparatively large degree of organizational concentration across the three sets of total topical patents, main path patents and start patents. This is mainly due to the French late-stage startup Carbios, a technology leader in the field, having built a comprehensive patent portfolio: half of the 20 high-impact start patents were filed by Carbios, which is thus identified as a key player in shaping the enzymatic recycling trajectory. While jurisdictional concentration is overall more homogeneous across topics than organizational concentration, it interestingly is *higher* for the full sample of recycling patents. This is likely a consequence of Chinese patents, the largest group within the full sample, being less dominant in the more selective topical subsets.

Third, the three topics vary with respect to main path structure. While the separation and textiles networks are separated into multiple disconnected components, the components apart from the main component are small and topically not clearly separated. For the enzymes main path, separation into two disconnected components (Fig. 3, bottom panel) is however also reflected in the patented technologies within the two components: The larger one contains chiefly the recent patents in the Carbios portfolio, which is primarily concerned with PET/polyester recycling and the means by which to achieve it, such as the development of new esterase enzymes and polypeptides with degrading capabilities. The second component, on the other hand, is primarily concerned with the devulcanization of rubber and prominently features the Goodyear tire company.

As measures of the overall degree of connectivity within each topic, we use the network diameter (i.e., the longest path among any two nodes in a network, representing visual ‘branchiness’ in Fig. 3) and the mean of the pairwise geodesic distances (i.e., the number of steps along the shortest path between two nodes) among the start patents in the main path. If the patents on the main path (or only the start patents in

Table 1

Summary statistics for selected recycling topics.

Statistic	Total	Textiles	Separation	Enzymes
Families	61,321	807	1491	234
Publication date (median)				
Total	2016	2013	1999	2018
Main path	2007	2001	1999	2004
Start patents	2018.5	2015	2000.5	2015.5
Applicant concentration (HHI)				
Total	0.00016	0.00306	0.00141	0.01549
Main path	0.00947	0.00761	0.01092	0.03702
Start patents	0.055	0.085	0.055	0.195
Jurisdiction concentration (HHI)				
Total	0.15124	0.07807	0.07341	0.10601
Main path	0.08432	0.09232	0.07631	0.09167
Start patents	0.09991	0.16078	0.05615	0.10348
Main path structure				
Components	5	3	3	2
Diameter (main component)	52	45	30	19
Mean geodesic distance (start pat.)	19.71	18.79	12.51	8.1
Mean forward citations	25.6	26.57	32.44	19.98
Topic homogeneity (% topical)	–	21.8	37	42.7

Note: Metrics are separately reported for all patents in a subdomain (total), for all patents on the main path, and for the 20 start patents. Topic homogeneity refers to the percentage of patents in the main path network that share the CPC classes used to identify the respective start patents.

the case of the latter statistic) are highly clustered, this will reflect in low scores on these metrics.

Especially textile recycling stands out with a large diameter of 45 and higher mean geodesic distance compared to the other two topics. Looking at Fig. 3, we can see that indeed many of the start patents sit on branches representing different kinds of textiles or related processes, such as continuous filaments, artificial turf, carbon fibers, or non-wovens for sanitary use, which only connect relatively far back through a ‘shared history’. Overall, the two measures then capture the degree of internal heterogeneity for this case. Interestingly, textile recycling also scores less in terms of topic homogeneity, i.e., the share of patents on the main path with the respective topic CPC labels, than the other topics. This is likely related to the fact that many of the start patents bring their ‘own history’ of non-textile historical antecedents, as indicated by the large diameter.

To summarize, comparison of the three examples reveals heterogeneity with respect to organizational composition as well as main path structure. On one end of the spectrum, enzymatic recycling, a very recent approach focused on depolymerization via biological processes, is topically homogeneous, dominated by a single patent portfolio, and it exhibits a strongly clustered main path structure. At the other end, the application field of textiles is topically more heterogeneous than the other subdomains due to the inclusion of different fiber-based materials. This heterogeneity is also represented structurally by a more ‘long-armed’ main path network (i.e., high diameter and start-to-start geodesic distances). Finally, separation is somewhere in between the other domains in terms of structural cohesion while being the most mature as well as the least concentrated in terms of applicant organizations.

4.3. *Interrelated technology evolution in the combined main path network*

So far, we have treated the three topics separately. However, they are not: As argued in the introduction, technological development is often linked across related domains. To capture this kind of interdependence, we create an integrated or combined main path network by initializing the main path traversal at the union of the start patents from the three topics. This way, patents from one topic can be encountered on forward or backward paths from/to patents in another topic. Looking at Fig. 4, the degree to which enzymatic recycling is disconnected form the other topics becomes quite clear: the only connection is through a ‘common ancestor’ while none of the enzymatic recycling start patents are on a direct path to or from the start patents in the other fields (Table 2B). The separation between the topics is also evident from the high mean (undirected) geodesic distances between the start patents in enzymatic recycling and the start patents in the two other topics (Table 2A), which is more than double compared to the score between the textiles and separation domains. This structural disconnect is plausible from a technological standpoint: While most of the predominant recycling technologies are rooted in mechanical engineering and classical polymer science, enzymatic recycling is rooted in biotechnology and thus builds on a different knowledge stock.

Textile recycling and separation technologies, on the other hand, are much more integrated. Many separation patents (13 out of 20, or 65%) are located on backwards paths for the textile recycling start patents (i.e., for many of the textile start patents, there is an ancestor on the main path that relates to separation technologies, Table 2B), indicating a flow of knowledge from the former to the latter. This is however not the case the other way around, with only a single textile patent being backwards reachable from a separation patent. Accordingly, developments in separation techniques seem to serve as a precondition for many textile recycling technologies. Indeed, upon closer inspection some of the separation patents address issues such as reclaiming of carpet components, indicating co-development of specific applications and process stages, such as textile recycling and separation techniques. Here again, the structural importance of single patent portfolios becomes apparent, with e.g., Mohawk Industries, a world leader in flooring and carpets, taking a leading role in both the separation and textiles fields. Overall, the metrics considered here reveal a variegated structure of interrelation between the three technological subdomains of recycling, with enzymatic recycling being largely independent of the other domains and a unidirectional historical dependency of more recent developments in textile recycling on earlier advancements in separation techniques.

5. Discussion

In this paper, we have studied the structure of technological co-evolution in the field of plastic recycling, using textile applications, separation techniques, and enzymatic recycling approaches as example subdomains. We use an original research design based on patent-based main path analysis to explore (a) structural differences and (b) structural interdependencies (or the lack thereof) between these technology domains. First, the three domains differ with respect to main path connectivity, topical homogeneity and the organizational concentration of innovation activity: Enzymatic recycling, a comparatively young technology domain, is characterized by a high degree of organizational concentration, topical homogeneity and strong connectivity between major patents (induced by high portfolio concentration), characteristics which might more generally be indicative of early-stage technologies. Textile recycling, at the other end of the spectrum, is characterized by topical heterogeneity, a lower degree of organizational concentration and low connectivity between high-impact patents, which indicate a more diversified domain combining different specialized fiber application contexts. Second, the analysis indicates patterns of technological (in)dependence in the evolution of the three domains. In an integrated main path representation, enzymatic recycling, an approach based in biotechnology, is largely disconnected from the other two domains, which in turn are characterized by a unidirectional historical dependence of textile recycling applications on separation techniques. While only representing a small excerpt of all technological approaches in plastic recycling, these results provide insights into a technological field which is characterized by both long-term historical interdependencies as well as recent approaches with disruptive potential, which however have not yet reached full maturity and do not yet interface with some of the core issues in the field.

On a more methodological note, our study shows how main path

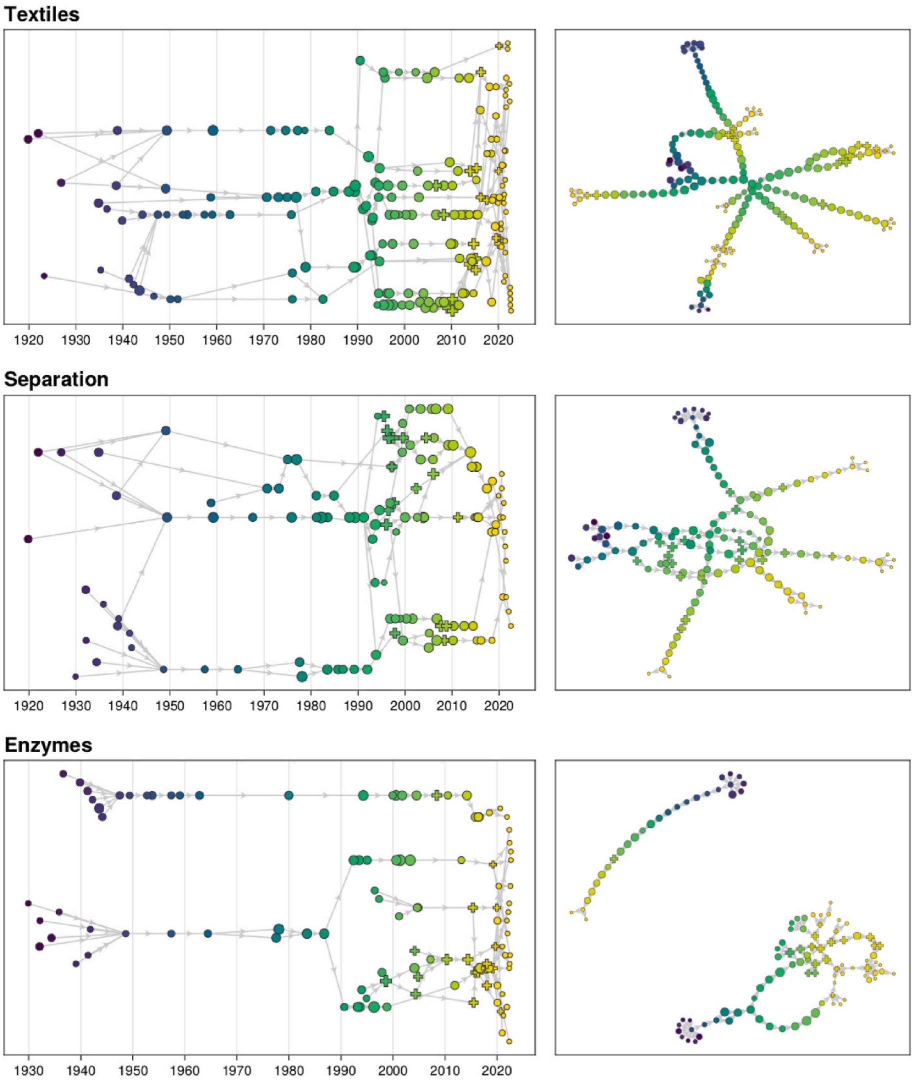

Fig. 3. Main path network for selected recycling technologies where arrows represent the forward flow of knowledge (i.e., the opposite direction of a citation). Sugiyama (left) and Kamada-Kawai (right) layouts to highlight different structural aspects. 'Plus' markers indicate start patents for main path traversal. Colors represent the earliest filing date of a patent and are the same across the two columns such that the panels to the left can serve as a legend. Node size reflects a patent's forward citations. Only main component shown for textiles and separation technologies. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

analysis initialized to capture multiple technologies of interest can be combined with simple and well-known network analytical procedures, such as reachability analysis and geodesic distances, to gain insights into the interdependent development of related technologies. We believe that this approach is a promising research avenue for the future, which might ameliorate some of the problems with main path analysis: past applications of the method usually have taken the resulting main path and its constituent patents as an accurate representation of the major developments in the underlying technological field to be studied qualitatively (Fontana et al., 2009; Mina et al., 2007; Verspagen, 2007). However, this has been shown to not always be the case (Filippin, 2021). By shifting the focus from in-depth, qualitative analysis of singular main paths as a faithful representation of technological trajectories to more structural analysis of heterogeneous main path networks as 'filtered' representations of the underlying citation network, some of the interpretive challenges with the former approach might be avoided.

Nevertheless, several limitations of the approach remain. First, it is a well-known fact that patents do not fully cover innovation activity, with other strategies to manage intellectual property or freedom to operate available (such as secrecy). While this can be argued to be less detrimental if there are no systematic differences in the rate of patenting across innovation contexts, this is not guaranteed: There could, for example, plausibly be differences between more mature and emerging technologies, which could bias implications drawn from structural analysis in unforeseen ways. More research to assess and anticipate these effects is needed. Second, the approach presented here relies on researcher-specified heuristics to initialize the algorithmic extraction of the main path as a reduced-form representation of the citation network. This also includes the procedure used to select the set of studied patents, which in this case made use of CPC classes only, but which could additionally employ keyword queries against patent contents or more advanced procedures, such as automated patent landscaping (Abood and Feltenberger, 2018). Methodological research on the sensitivity of the approach to different parametrizations would be valuable, e.g., regarding the quantity and selection criteria for the start patents used to initialize the main path traversal. Third, the current approach is descriptive, and the meaning and relevance of structural features is largely anecdotal. Future studies that connect the approach outlined here to different measures of industrial dynamics could help to identify and stabilize the interpretations of structural features of main path

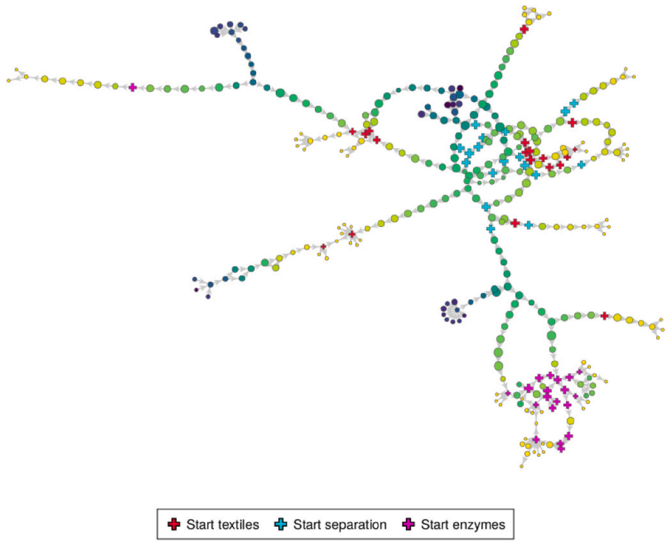

Fig. 4. Combined main path network (only the two largest components are shown). Base color and node size represents publication date and forward citation count, as in Fig. 3. Plus symbols represent start nodes. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Pairwise main path connectivity for topics.

	Geodesic distance (A)			Backwards reachability (B)		
	T	S	E	T	S	E
Textiles	13.5	11.5	26.1	–	0.65	0.00
Separation	–	7.7	24.2	0.05	–	0.00
Enzymes	–	–	7.5	0.00	0.00	–

Note: Panel A shows mean undirected geodesic distances between the start patents in each topic. Panel B shows the share of the k = 20 start patents in a topic (column) that are reachable from a start patent in another topic (row), where a patent x is reachable for a patent y if there is a path of citations leading from x to y.

networks.

6. Conclusion

The fundamental idea of path-dependent and interrelated technological change is well theorized in the evolutionary economics of Dosi and Nelson (2010), and the patent-based main path analysis proposed by Verspagen (2007) represents an interesting approach for its direct empirical operationalization. The present study builds on this operationalization to quantify structural features of interrelated development in heterogeneous technological fields. While we believe this approach to be a step towards a more comparative study of technical change that contrasts the dominant mode of idiosyncratic historical analysis, theoretical substantiation of specific structural features and the conditions under which they occur remains largely an open problem. In this vein, promising research avenues involve the cataloging of typical or otherwise prominent structural features in technological change, such as junctures or patterns of convergence and divergence, and their associated theoretical mechanisms leading to their emergence.

The approach discussed here also has some implications for policy and strategic decision-making: First, in-depth understanding of the structure of interrelated technology domains and their interdependencies can aid in the identification of bottleneck technologies or bridging/enabling technologies (and the respective dominant actors). These in turn can be important targets for policy to spur development of a larger field through targeted support or for corporate innovation strategy to enable early adoption and the occupation of key ‘technology niches’. In the case studied here, separation techniques occupy the role of enabling technology for downstream inventions in textile recycling and could thus be taken as an entry point for a more comprehensive assessment of its potential as, e.g., a funding target. Second, the approach can aid in the identification of the technological contexts (and the key actors) from which new and potentially disruptive approaches emerge. If such new approaches are largely incompatible with existing knowledge bases, as is the case for enzymatic recycling techniques, incumbents in the field need to reevaluate their own position and knowledge stock and balance the risk of being ‘left behind’ against the risk of a premature lock-in (Frenken et al., 2004). In such a situation, having monitoring systems in place that shed light on how and where a new technology interfaces with existing ones is crucial, as is demonstrated by the wide-spread existence of IP screening systems for corporate innovation strategy.

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CRediT authorship contribution statement

Jakob Hoffmann: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Johannes Glückler:** Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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