



# Agricultural technology as a driver of sustainable intensification: insights from the diffusion and focus of patents

Yafei Li<sup>1</sup> · Felix Herzog<sup>1</sup> · Christian Levers<sup>2,3</sup> · Franziska Mohr<sup>4,5</sup> · Peter H. Verburg<sup>2</sup> · Matthias Bürgi<sup>4,5</sup> · Rebekka Dossche<sup>4,6</sup> · Tim G. Williams<sup>2</sup>

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## Abstract

Sustainable intensification (SI) responds to the concurrent challenges of increasing food production while reducing the environmental impacts of agriculture. As an early disclosure of innovation, patents are a useful indicator of technology market potential. However, we lack understanding of the extent to which current agricultural technology patents relate to the goals of SI and which kinds of technologies can potentially address SI. Here, we analyzed the diffusion and focus of more than one million patents issued during the period 1970–2022. We explored the degree to which the patents relate to SI through the co-occurrence of efficiency and environmental friendliness targets. Our results reveal that while the rate of patent issuance has dramatically increased over the past five decades, the rate at which patents diffused to different countries had decreased over time. The USA was the biggest net exporter of patents and had produced by far the most high-impact patents (in the top 1% most-cited patents). Since 1970, only 4% of agricultural patents and 6% of high-impact patents were related to SI targets (i.e., promoting both agricultural efficiency and environmental friendliness), but the attention to SI has increased over time. The most highly cited SI-related patents had become more diverse over time, shifting from digital, machine, and energy technologies in 1980s to the current era of agroecology, information, and computer networking. Our results provide an early indication of promising technologies that may play a greater role for SI in the future, subject to the challenges of market transfer and farm adoption and complemented by non-technological innovations in farm management and institutional support.

**Keywords** Farm technology · Patent review · Precision farming · Digital technology · Machinery automation · Renewable energy

## 1 Introduction

Agriculture faces the intertwined challenges of increasing food demand, climate change, and limited resource and land availability (Basso and Antle 2020). Sustainable intensification (SI) has raised considerable interest among different stakeholders due to its ambition to simultaneously support agricultural production and environmental sustainability (Tilman et al. 2011; Garnett et al. 2013; Godfray and Garnett 2014; Godfray 2015; Helfenstein et al. 2020). SI measures take three main forms: improving efficiency, substitution, and system redesign (Haughey et al. 2023). Improving efficiency has traditionally been the focus of agricultural research and industry (Haughey et al. 2023). Substitution and system redesign, in contrast, relate more closely to the actual farm management regarding the replacement of agricultural inputs (e.g., agro-chemicals)

✉ Yafei Li  
yafei.li@agroscope.admin.ch; l.yafei@outlook.com

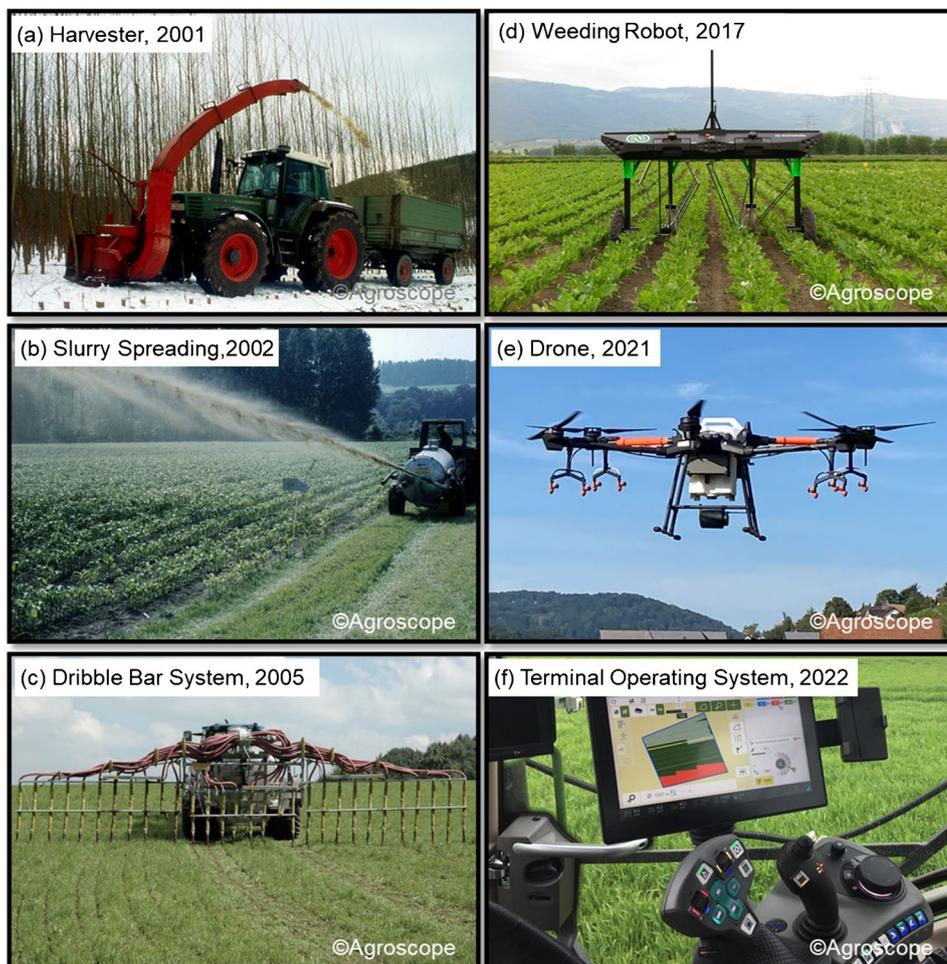
- <sup>1</sup> Agroecology and Environment, Agroscope, Zürich, Switzerland
- <sup>2</sup> Environmental Geography Group, Institute for Environmental Studies (IVM), VU Amsterdam, Amsterdam, The Netherlands
- <sup>3</sup> Thünen Institute of Biodiversity, Johann Heinrich von Thünen Institute - Federal Research Institute for Rural Areas, Forestry and Fisheries, Braunschweig, Germany
- <sup>4</sup> Land Change Science Research Unit, Swiss Federal Research Institute WSL, Birmensdorf, Switzerland
- <sup>5</sup> Institute of Geography, University of Bern, Bern, Switzerland
- <sup>6</sup> Department of Antiquities, Philosophy, History and Geography (DAFIST), University of Genoa, Genoa, Italy

and major system changes (e.g., turning to organic farming, adopting intercropping methods).

To move towards agricultural SI requires a range of actions (Vanlauwe et al. 2014; Petersen and Snapp 2015; Struik and Kuyper 2017; Weltin et al. 2018): landscape management, policy making, regional integration, and technology innovation. Based on a literature review, Weltin et al. (2018) defined four kinds of action fields to reach SI: agronomic development (breeding, data-based farming, soil tillage and conservation, adapted cropping, as well as animal husbandry and grazing), resource use efficiency (fertilizer, water, fodder, residue, energy, knowledge, labor, additive, general resources, and soil management system), land use allocation (land sparing and land sharing), and regional integration (knowledge and innovation diffusion, improving institutions, network and social capital, lobbying awareness raising, as well as regional marketing and value creation). The improvement and transfer of agricultural technology (Fig. 1) can potentially play a role in advancing SI through supporting agronomic development, improving resource use efficiency, and optimizing land use allocation.

Patents are an important precursor to future technology and thus provide an indication of the direction and focus of future technology innovation (i.e., novel actions to improve a product, process, or service). As the bedrock of innovation, an invention is a new solution to technical problems. Patents are one form of intellectual property rights to protect inventions. Patenting makes information widely available and thus sparks new ideas and promotes more innovation (WIPO 2023a). Therefore, patents are a rich data source for studying and predicting technological innovations (Ernst 1997). Patents are valid at the national level, so inventors are inclined to protect high-quality inventions (Gao and Zhang 2022) in different countries by applying to grant their patents in different national and/or regional patent offices, such as the United States, China, or the European Patent Office. Patent application in foreign patent offices (different from the country of origin, termed “priority country”) is driven by two motivations: to exploit the patent in international markets with potential demand of the inventions and to protect high-quality inventions (Beneito et al. 2018).

**Fig. 1** Images of exemplary of agricultural technologies in the past decades.



Yet, it is important to note that patents provide only a partial picture of technological innovation. Besides patenting, innovations can also be protected by registering trademarks and copyrights (United States Patent and Trademark Office (USPTO) 2021). Patents generally provide 20 years of protection and are thus a good way to protect technological innovation at an early stage, before the technology is transferred to the market, especially for innovations with long-term development cycles (Seip et al. 2018). Trademark protection, in contrast, can last as long as the trademark owner uses it in commerce (Stim 2022), but a trademark has to be marketed within 5 years of application (Seip et al. 2018). Further, not all technological innovations are necessarily formally registered, as technology designed by farmers may be first applied in the field for many years before being registered as patents/trademarks (FarmHack 2013; Ensor and de Bruin 2022). Our analysis is limited to technology that has been formally registered, whereas farmer-led research and development is not necessarily legally protected or even intentionally kept in the public domain to make it easily accessible (e.g., Doornbos 2001; see also Kotschi and Horneburg 2018 on the issue of public domain patenting). Finally, patents do not inform about national diffusion of technology and do not necessarily always lead to technology transfer in the market and adoption by farmers or contractors due to a wide range of socioeconomic barriers (e.g., more than 95% of all patents are never commercialized; Adenle et al. 2012; Peschard 2014; Walker 2014; Qaim 2020). For instance, public resistance to genetically modified organisms in Europe and Africa has inhibited the adoption of these technologies in these places (Evenson and Gollin 2003; Qaim 2020). This does not mean patents are worthless (Panitch 2020); many researchers use patents as a source of technological information, and patent disclosure can have informative benefits across a broad range of technologies (Ouellette 2011; Baruffaldi and Simeth 2020; Büttner et al. 2022) and promote the increasing patenting (Furman et al. 2021). Patent citations are an indicator to predict the patent market values (Owen-Smith and Powell 2003; Hall et al. 2005) and have been used to determine the innovative levels of patent technologies (Park et al. 2023).

Patent reviews are useful for synthesizing the general technological developments in a field. Existing patent reviews focus on specific fields of agriculture, e.g., biotechnology (Foltz et al. 2000, 2003; Taylor and Cayford 2003), nanotechnology (Yata et al. 2018), new plant varieties (Rickard et al. 2016), green agriculture (Hu and Xu 2022), intelligent agriculture (Ren et al. 2017), and climate change adaptation (Auci et al. 2021). Others analyze specific regions, e.g., the US (Sokoloff 1988; Taylor and Cayford 2003), China (Liu et al. 2014), India (Mittal and Singh 2006), Brazil (da Silveira et al. 2021), Europe (Auci et al. 2021), and Africa (Taylor and Cayford 2003). Existing research also addresses the social and economic aspects of patents, e.g., Research and Development

(Johnson and Evenson 1999; Penner-Hahn and Shaver 2005), patent licensing programs (Rubenstein 2003), patent policy (Taylor and Cayford 2003), patent sociology (Pechlaner 2010), and company' patenting decisions (Chan 2010). An integrated agricultural patent review based on patent descriptions could provide insights into future technology innovation and indicate what kind of technologies can potentially support agricultural SI. This has, however, not yet been done due to the lack of readily available lists of agricultural patents and the complexities of linking patents to agricultural SI.

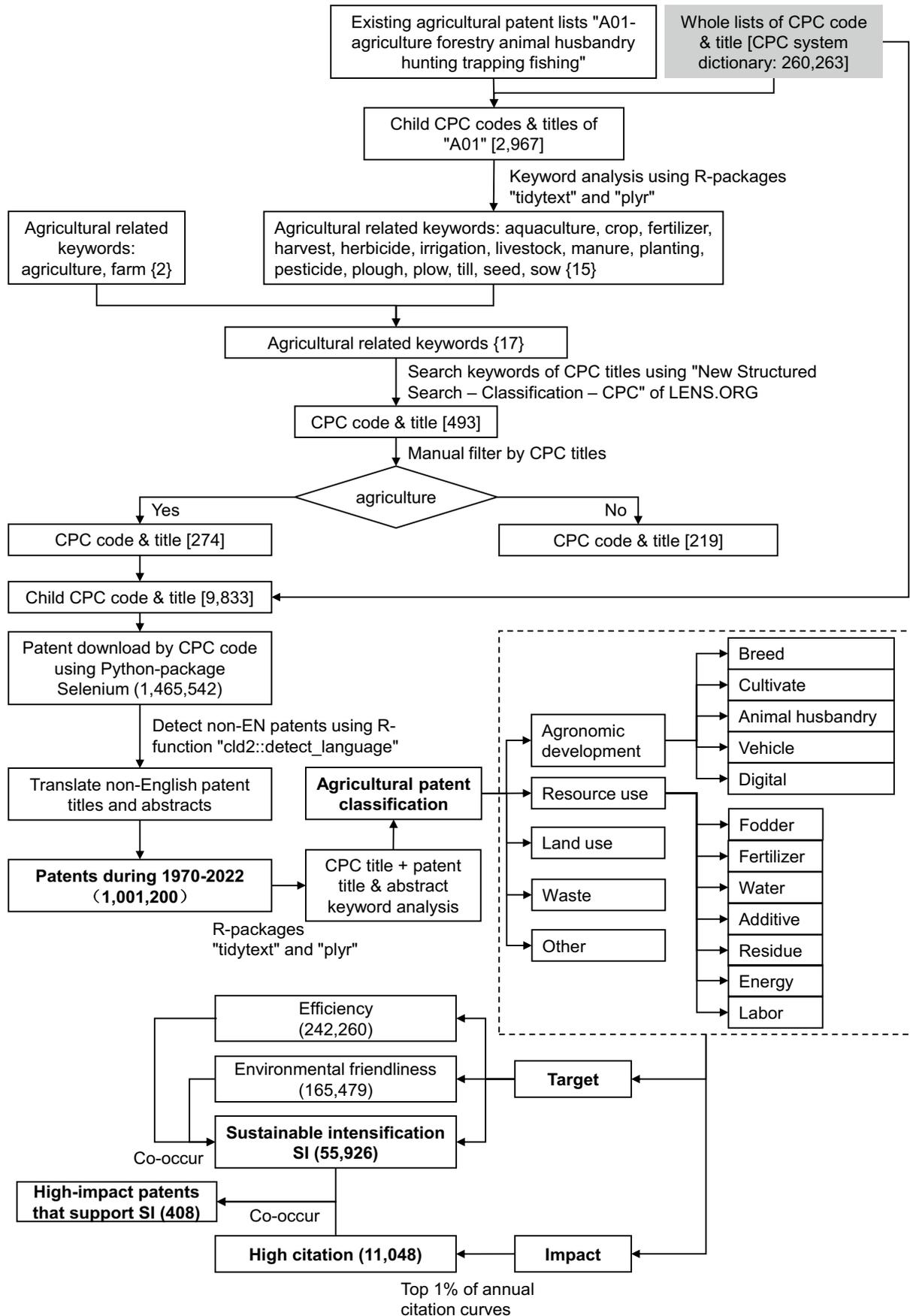
In this study, we explored the diffusion and focus of agricultural patents as indications of the potential for the different types of technologies to support SI (Fig. 2). We defined this relation as the co-occurrence of "efficiency" and "environmental friendliness" themes, i.e., as technologies that related to both aspects simultaneously. Our study addressed the following research questions:

1. How has agricultural technological innovation been reflected in the issuance and diffusion of patents in general and high-impact patents in particular over the past 50 years?
2. To what extent are agricultural patents related to different agricultural action fields and SI?
3. What kinds of high-impact patents support agricultural SI targets?

## 2 Methods

### 2.1 Patent classification systems

There are three kinds of widely used patent classification systems: the International Patent Classification (IPC; WIPO 2023b), the United States Patent Classification (USPC; United States Patent and Trademark Office (USPTO) 2023), and the Cooperative Patent Classification (CPC; European Patent Office (EPO) 2017). The CPC system is jointly developed by the European Patent Office (EPO) and the United States Patent and Trademark Office (USPTO). CPC is a more specific and detailed version of the IPC system. In July 2013, Europe and China agreed to use the same CPC system (European Patent Office (EPO) 2013), and old patents were also transferred and coded within the CPC. In this study, we used the CPC system for the search and classification of agricultural patents. CPC systems classify patents into nine different sections coded as A–H and Y, which in turn are sub-divided into classes, sub-classes, groups, and sub-groups (European Patent Office (EPO) 2017). As a result, there are 260,263 unique classification entries in the CPC system (as at August 2022; item numbers may vary depending on the version of the CPC system; European Patent Office (EPO) 2022). An upper-level classification is termed "parent classification," and a lower-level classification is termed "child classification."



**Fig. 2** Filtration and classification of patents. Patents were related to sustainable intensification (SI) through the targets of efficiency and environmental friendliness. High-impact patents were defined as those with the top 1% most citations. Values in brackets “( )”, “[ ],” and “{ }” indicate the number of patents, of CPC (Cooperative Patent Classification) lists, and of keywords, respectively. Whole lists of CPC codes and titles (gray shaded boxes) act as the dictionary to find the child lists of their parent CPC lists.

We manually selected the parent CPC lists that directly mentioned agriculture-related keywords in CPC titles and then extracted the corresponding child lists according to the whole CPC lists (260,263 items; European Patent Office (EPO) 2022; Fig. 2). This was necessary, as the existing agriculture patent CPC code “A01-agriculture forestry animal husbandry hunting trapping fishing” did not cover all the agriculture-relevant patents as indicated in the titles of its sub-classifications (e.g., fertilizers are in the classification of “C05”). Furthermore, we refrained from a simple, direct keyword search based on patent titles and abstracts to identify relevant patents because of three main limitations: (1) It can retrieve irrelevant patents to the focal technology action field (e.g., when searching “irrigation”, patents related to oral medical irrigators may also be retrieved). (2) There is no proper way to choose keyword lists that can cover all relevant patents. (3) Multilingual patents cannot be covered by English keyword searching if they are not translated into English in the patent dataset.

With detailed classification systems, CPC titles provide a good approach to search agricultural patents (Block and Song 2022). The grouping of similar patents in CPC systems allows covering other related patents by providing only a small number of keywords (e.g., “herbicide” was classified in the CPC titles of “herbicides, pesticides, fungicides, insecticides, or the like”, which automatically covers “pesticides”, “fungicides”, and “insecticides” despite that we only included “herbicide” in our selected keywords). In addition to “agriculture” and “farm” as direct keywords indicating agricultural patents, we analyzed the keywords of child CPC titles of the existing agriculture patent CPC “A01” using R packages “tidytext” and “plyr” and manually selected another 15 keywords that indicate agricultural technologies: aquaculture, crop, fertilizer, harvest, herbicide, irrigation, livestock, manure, planting, pesticide, plough, plow, till, seed, and sow. These 17 keywords were searched using the “New Structured Search – Classification – CPC” function on the website of Lens.Org. With this initial search, we obtained 493 CPC codes/titles for agricultural patents. The “stemmed” function of Lens.Org allows covering all relevant wildcards of our defined keywords (e.g., the wildcard of “irrigation” is “irrigat”, which captures the patents including “irrigate”, “irrigates”, “irrigated”, “irrigation”, “irrigating”, and “irrigator”, among others). We manually filtered out all CPC codes/titles that did not explicitly address agriculture in their parent or child CPC titles, which resulted in 274 parent CPC

codes/titles related to agricultural technology. The CPC titles/codes have six levels from broader to more detailed classifications (e.g., “A”–“A01”–“A01B”–“A01B1/00”–“A01B1/02”–“A01B1/022”). To extract every-level CPC groups of a patent, we searched for the child CPC codes/titles of the 274 parent CPC codes/titles in the entire CPC list (260,263 items; European Patent Office (EPO) 2022), until no child CPC codes/titles were found (e.g., until “A01B1/022” there is no child CPC anymore). Finally, we obtained a list of 9833 child CPC codes/titles for agricultural relevant patents. These CPC lists were used for patent download with the Python-package “Selenium” in Jupyter Notebook (Kluyver et al. 2016). We obtained a total of 1,465,542 patents. Each patent has a unique “LENS\_ID” (e.g., “049-630-071-585-62X”), which allows eliminating duplicates. Using the R-function “cld2::detect\_language” for analyzing the titles and abstracts of the obtained patents, non-English patents were extracted and translated using “Google Translate.” The non-English titles and abstracts were replaced by the translated English versions through identifying the corresponding patents using the unique “LENS\_ID” for each patent. We focused our study on the period from 1970 to 2022, as patent searching systems converged in the 1970s and the online patent search started (United States Patent and Trademark Office (USPTO) 2019), which resulted in 1,001,200 patents that we used for our analysis.

## 2.2 Patent keyword classification

We adopted the existing framework of sustainable intensification by Weltin et al. (2018) to classify patents as relating to five main agricultural action fields: agronomic development, resource use, land use, waste, and other (Fig. 2). Furthermore, Weltin et al. (2018) mentioned that resource use efficiency includes the sub-classification of residues, from which we interpreted a broader concept of “waste,” and listed out this category including greenhouse gas emissions, general waste, and atmospheric particulate matters (Table 1). Agronomic development and resource use were further classified into sub-categories (Fig. 2). Packing, device making, device checking, and other minor categories of patents (Table 1) were assigned to the category of “other” (e.g., “Convolved Boot” was classified in CPC “B29L2031/70: agricultural usage or equipment,” but did not have related descriptions that can group it into a specific category that we defined; Schafferus and Mueller 1992).

Patents of different classifications were assorted in R (R core team 2022) by conducting the keyword analysis of CPC titles to which a patent belongs, combined with individual patent titles and abstracts using R packages “tidytext” and “plyr”. The wildcards, i.e., parts of keywords (e.g., “comput” representing the keywords of “computer”

**Table 1** Patent classifications by the keyword analysis of Cooperative Patent Classification (CPC) titles and titles and abstracts of individual patents. The wildcards of the keywords used for assorting patents follow the expression of R; they are sorted by their frequency and synonyms are joined.

Patent classification	Keywords (wildcards) used for assorting patents	
Agronomic development	Breed	gene, variet*, biotech, mutation, breed, transgenic
	Cultivate	soil working, sow, seeding, seeder, harvest, horticulture, threshing, plant husbandry, planting, tillage, harrow, plough, plow
	Animal husbandry	fish, aquaculture, livestock, dairy
	Vehicle	vehicle, tractor, truck, robot, aircraft, drone, vessel, boat, ship
	Digital	comput*, digit, data, communicat*
Resource use	Fodder	fodder, feed, graz*
	Fertilizer	fertilis*, fertiliz*, compost, manure, dung
	Water	(?!de-)watering, irrigat, water.sav, sav.water, water.conservanc, conservac.water
	Additive	pesticid*, herbicid*, biocid*, antibioti*, additive
	Residue	residu*
	Energy	energ, power, electri, wind(?!ow, ing), hydrau*, solar, fuel
	Labor	labor(?!at), labour
Land use	Land use	land use, landuse, landscape, building, housing, road, railway, glasshouse, glass house, green house, greenhouse(?! gas), corridor, fence, river, hard structure, dams, artificial reef
Waste	Waste	emission, greenhouse.gas, waste, atmospheric particulate matter
Other	Other	packing, device making, device check, and other unspecific patents

and “computing”, among others), used for patent assorting are listed in Table 1. Irrelevant matches of wildcards were excluded (e.g., wildcard “(?<!de-)watering” excluding “de-watering”, Table 1). Some of the patents belong to multiple classifications in agricultural action fields. We counted these patents in each agricultural action field they belong to, because knowledge can serve multiple purposes simultaneously, and patents that serve multiple agricultural action fields contribute simultaneously to the different agricultural classifications (Hötte and Jee 2022). For instance, “digital-control water-saving irrigator” contributed to water saving and digital technologies and was thus classified in both “resource use: water” and “digital” categories. We used multiple classifications of a single patent based on the fact that multiple classifications also occurred in CPC systems. For instance, a patent called “Fodder Production Apparatus and System” was classified

into CPC categories of “A01G31/06” (hydroponic culture on racks or in stacked containers), “A01G9/143” (equipment for handling produce in greenhouses), “Y02A40/25” (greenhouse technology, e.g., cooling systems therefor), and “Y02P60/21” (dinitrogen oxide (N<sub>2</sub>O), e.g., using aquaponics, hydroponics, or efficiency measures).

Patents that support the transition towards SI should both relate to the efficiency of agricultural production processes and be environmentally friendly (Haughey et al. 2023; Weltin and Hüttel 2023). The keywords (wildcards) used for assorting “efficiency” and “environmental-friendliness” patents (Table 2) were selected through keyword analysis of patent titles and abstracts complemented by expert knowledge of our co-authors (brainstorm approach proposed by Li et al. 2009). In this study, we consider patents to relate to SI if they match both “efficiency” and “environmental-friendliness” keywords.

**Table 2** Keywords used for assorting the patents related to the targets of efficiency, environmental friendliness, and sustainable intensification (SI). The wildcards of the keywords used for assorting patents follow the expression of R; they are sorted by their frequency and synonyms are joined.

Target	Wildcards
Efficiency	efficien, effective, sufficien, substantial, improv, return on investment, save, saving, conserv(?!ancy), precis, accura
Environmental friendliness	ecolog, biodive, degrad, renewable, zero.till, reduced.till, no.till, recyc, electri, wind(?!ow, ing, screen, row), hydrau, solar, pneumat
Sustainable intensification (SI)	Occurrence of both efficiency and environmental friendliness keywords

### 2.3 Evaluation metrics of patent review

We used patent issuance, diffusion, and citation as evaluation metrics to assess technology innovation. Patent issuance was quantified by the temporal and spatial variability of numbers of patent issuance, patent priority, and patent grant. Patent diffusion was quantified by patent diffusion numbers, patent diffusion rate, and priority-to-publishing duration. Patent citation was quantified by the number of patents that cite the focal patents. “Patent priority” is an indication of technology innovation in the country where a patent was first registered (Nagaoka et al. 2010), while “patent grant” is a sign of technology market potential in the issued country of a patent (Livotov 2015). “Patent diffusion” is defined as the granting of patents in countries different from their priority countries. The priority numbers in the patent dataset indicate the country that owns the priority of a patent, while the application numbers indicate the countries (or regional patent offices) where a patent was granted or issued. Patent rights are territorial; hence, patents with the same priority

code can have multiple application codes, indicating that they were granted in different countries to protect their innovation nationally or regionally. We removed any potential patent replicates when calculating the numbers of patent priority and diffusion by using the unique “LENS\_ID” of each patent.

The earliest date of priority is defined as the earliest date of filing a patent application, anywhere in the world, to protect an invention (Lens.Org 2022). We defined publication duration as the period from the earliest date of priority to its publication date in a specific country. The duration from earliest priority to the publication of a patent in a particular country reflects the diffusion speed of a patent. NOP refers to the number of patent priorities, while NOD refers to the number of patent diffusions. Therefore, the patent diffusion rate (PDR), which provides an indication of the average international dissemination of technology innovation for a particular country, is defined for a particular country as the ratio of NOD to NOP (Pan et al. 2022), i.e.,

$$\text{Patent diffusion rate (PDR)} = \frac{\text{Number of patent diffusion (NOD) in a country}}{\text{Number of patent priority (NOP) in a country}}$$

A given patent that is granted from priority country A to country B is defined as the patent export of country A and the patent import of country B. Based on this definition, we used the patent right index (PRI), which is a composite index

reflecting international dissemination and market potential of technological innovation in a particular country, to quantify the patent-right balance of a country:

$$\text{Patent right index (PRI)} = \frac{(\text{export} - \text{import}) \text{ in a country}}{\text{patent export in the country with most patent exports}}$$

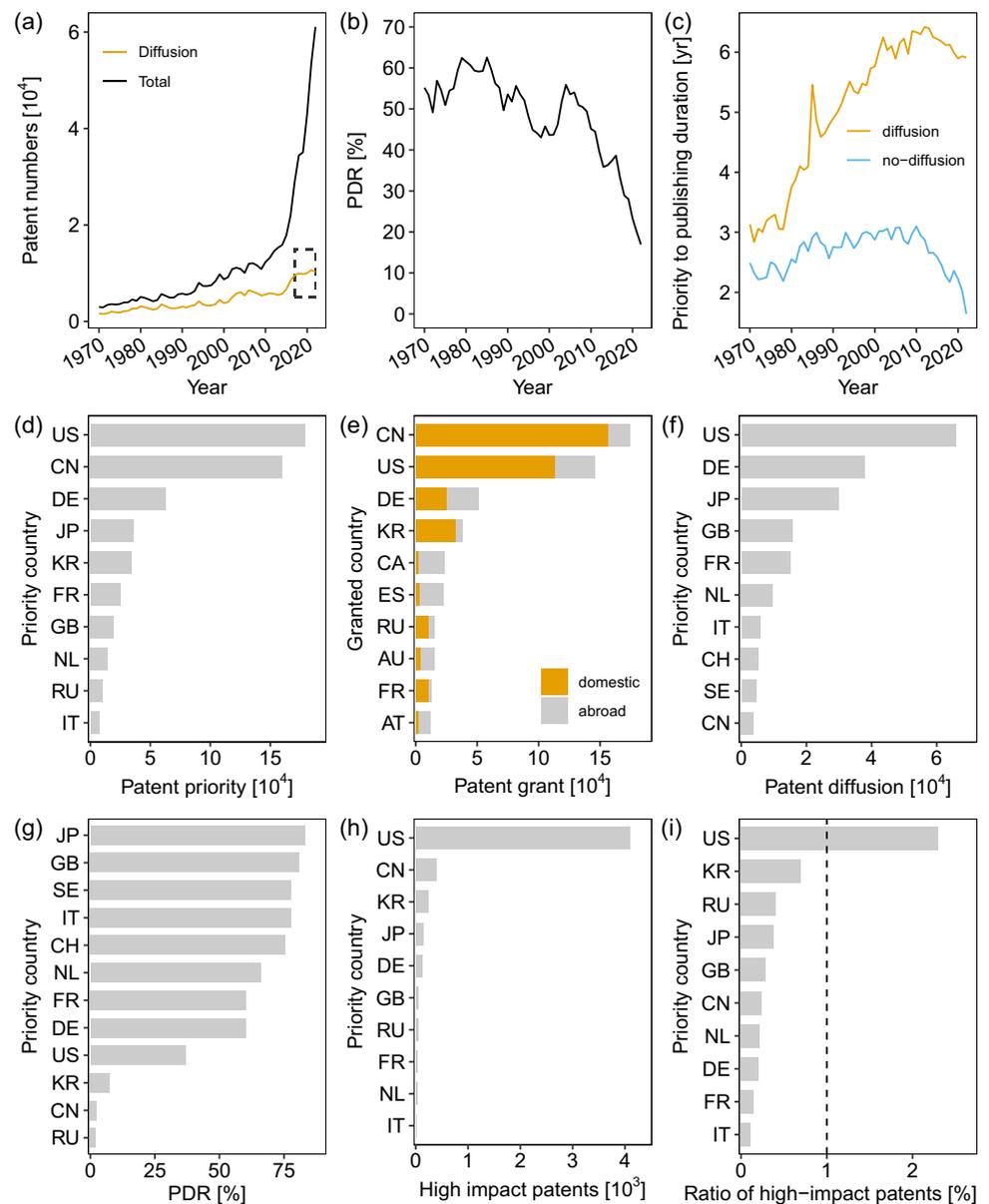
Patents usually cite other patents, and patents that are cited more frequently are considered to be high-impact (Hall et al. 2005; Park et al. 2023). We defined highly cited patents as high-impact patents, because patent citations act as an indication of patent market values and innovation levels (Owen-Smith and Powell 2003; Hall et al. 2005; Park et al. 2023), and every extra citation per patent will boost the market value by 3% according to Hall et al. (2005). Patents take time to be cited, and thus, recent patents have a relatively lower number of citations than past patents. According to Jaffe and Trajtenberg (2002), patent citations reach their peak after 5 years of issuance. To diminish the citation lag effect, we selected the top 1% of annual patent citation curves (ranked by patent counts that cite the focal patents) instead of using citation curves for the entire study period. A total of 6657 patents were selected as high-impact patents with citation numbers equal to or higher than citation thresholds in the corresponding year. The high-impact patents related to the SI target were manually classified according to patent titles and abstracts and considered the representative technologies of SI-related patents during each decade.

## 3 Results and discussion

### 3.1 Issuance and diffusion of patents and high-impact patents

The agricultural patent issuance and diffusion showed high temporal variability (Fig. 3). The number of issued agricultural patents steadily increased from 1970 to 2022, with a particularly dramatic rise over the past 10 years (Fig. 3a). Conversely, while patent diffusion numbers increased in the mid-2010s, they increased more slowly over the past 5 years (Fig. 3a). 38% of patents diffused to a different country over our study period, and PDR had been decreasing since the mid-2000s (Fig. 3b). The discrepancy between patent issuance and diffusion could be related to the fact that it takes longer for patents to be granted in foreign countries (3–6 years) than domestic issuance (2–3 years) (Fig. 3c). However, PDR began to decline already in the 2000s (Fig. 3b), suggesting other factors besides the time lag being responsible (Jaffe and Trajtenberg 2002). One possible explanation is the limited absorptive capacity (a company’s ability to recognize the value of new information,

**Fig. 3** Temporal and spatial dynamics of patent development and diffusion. **a** Annual patent numbers and patent diffusion numbers; the dash-line framed area corresponds to the last 5 years (2017–2022) with slowing increase of patent diffusion. **b** Annual values of patent diffusion rate (PDR), i.e., the ratio of patent diffusion numbers to total patent numbers. **c** Priority (earliest priority date) to publishing (publication date) duration for the patents that diffuse to other countries (abroad) and the patents that do not diffuse to other countries (domestic). **d** Top 10 countries with most agricultural patent priority. **e** Top 10 countries with most granted patents, i.e., the sum of domestic and abroad priority patents. **f** Top 10 countries with most diffused-patent priority. **g** PDR in the top 10 countries with most patent priority or diffused-patent priority (12 countries in total because of the repetition of two lists). **h** High-impact patent numbers in top 10 countries with most patent priority. **i** Ratio of high-impact patents in total patent priority in top 10 countries with most patent priority. Country codes are listed on European Patent Office (EPO) website: <https://register.epo.org/help?lng=en&topic=countrycodes>.



assimilate it, and apply it to commercial ends) of technology in recipient countries (Gao 2022), leading to patent diffusion not increasing in line with the total number of granted patents (Fig. 3a). Another reason could be that patents have become less disruptive, with fewer “low-hanging fruit” innovations available (Chu and Evans 2021; Park et al. 2023) and thus lower market potential to be issued abroad (i.e., lower diffusion rate).

The agricultural patent issuance and diffusion showed high spatial variability (Fig. 3). The US had the most patent priority followed by China (Fig. 3d). In contrast, China granted the most patents followed by the US (Fig. 3e), which corresponds to the report of overall patents that China became the top filer of international patents in 2019 (WIPO 2020). The fact that China and the US were the top two

countries of agricultural patent priority and issuance agreed with their leading positions in contemporary global food and agricultural networks (Veeck et al 2020). The spread of patents was most pronounced in the US, while the patent diffusion numbers were much smaller in China (Fig. 3f). Among the top-ten countries with most patents or patent diffusion (12 countries in total because eight countries appear on both lists), Japan, the UK, and Sweden had the highest PDR (Fig. 3g). Eighty-nine percent of patents granted in China were based on the domestic priority (i.e., had not previously been issued elsewhere; Fig. 3e), due to 25% of global patent priority owned by China (Fig. 3a). In contrast, higher proportions of foreign-priority patents were granted in Canada (91%), Spain (89%), Austria (80%), and Australia (76%) (Fig. 3e). The generally lower patent priority in

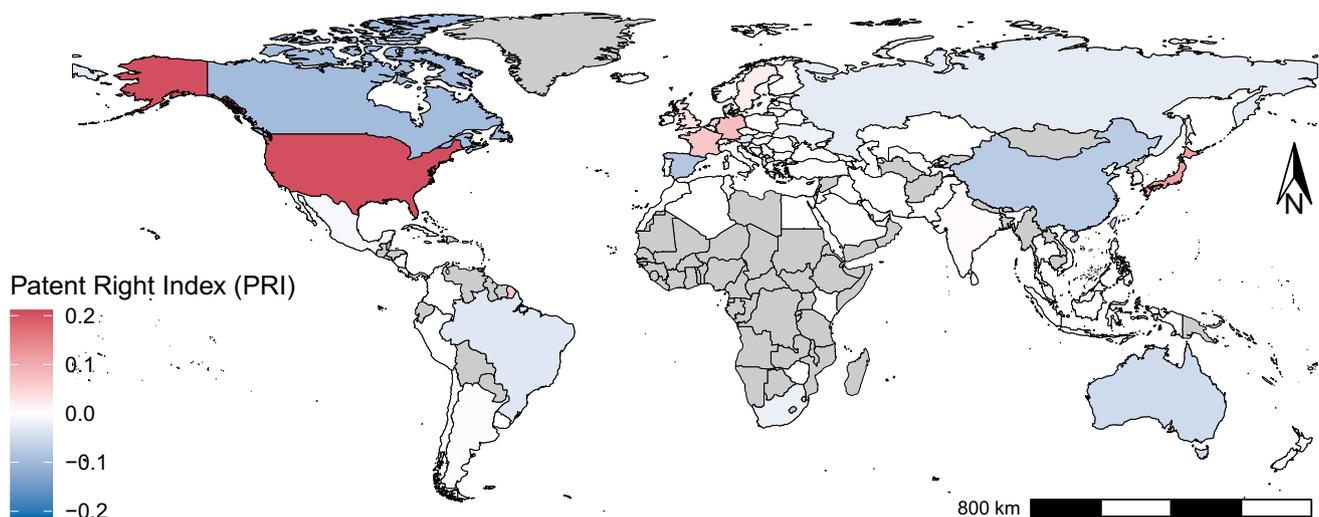
Europe (Fig. 3d) can be related to the expensive validation and renewal fees in the European Patent Convention (EPC) (Harhoff et al. 2009), which can limit patent issuance due to barriers deriving from the cost of patent offices, translation, and attorney (Harhoff et al. 2009; Liu et al. 2014), as well as lawsuit risks (Lanjouw and Schankerman 2004). Therefore, the expected benefits of patent issues need to offset the cost of additional fees and litigation risks.

The US had by far the most high-impact patents, followed by China, South Korea, Japan, and Germany (Fig. 3h). Among the total amount of patent priority in individual countries, high-impact patents occupied the highest ratio in the US, followed by Korea, Russia, Japan, and China (Fig. 3i). The high-impact ratios were higher than the threshold (1%) in the US, but lower in the other top 10 priority countries (Fig. 3i). Countries with higher PDR for total patents tended to have higher PDR for high-impact patents (Fig. S1), because inventors are inclined to protect high-quality inventions by granting their patents abroad (Beneito et al. 2018; Gao and Zhang 2022). This was not observed, however, in the US and in Australia (Fig. S1). The diffusion discrepancy between total patents and high-impact patents might be because patenting abroad can be affected by the efficiency of owners in protecting their rights (Lanjouw and Schankerman 2004) and the non-patenting way of protecting technology innovation (United States Patent and Trademark Office (USPTO) 2021). Patents owned by large corporations tend to be more valuable than those owned by small patentees (Bessen 2008), and large corporations are more efficient in protecting their patent rights (Lanjouw and Schankerman 2004). Besides patenting to protect technology innovation, the inventors may protect their technology

innovation by registering trademarks and copyrights (United States Patent and Trademark Office (USPTO) 2021). Due to the different regulations on protection and market transfer, companies are recommended to register trademarks if they can efficiently transfer the technology into commercial goods and services and keep their trademark rights as long as they use the trademark in commerce (Seip et al. 2018; Stim 2022). However, despite the 20-year patent protection period, it is recommended that innovations with long development cycles, especially those in the early stages, register for patent protection (Seip et al. 2018; Stim 2022).

The balance of patent exports and imports in a particular country is indicated in the PRI map (Fig. 4). Positive PRI indicates that countries exported more patents to foreign countries than they imported, which was the case for the US, Japan, Germany, France, the Netherlands, the UK, Sweden, Switzerland, Italy, and Finland, among others (Fig. 4). Conversely, negative PRI indicates that countries import more patents from foreign countries than they export, which was evident for Canada, Spain, China, Australia, Denmark, Austria, Brazil, Russia, South Africa, and Korea (Fig. 4). The US's role as a major patent exporter corresponded to its role as a major exporter of many crops (e.g., soybeans, wheat, corn, cotton, and rice) with 16.5% of the world's arable land but only 4.27% of the world's population (Paraskevopoulou et al. 2016; Veeck et al. 2020). In contrast, China's role as a major patent importer was driven by promoting the growth of domestic industries through absorbing foreign investors' advanced technology (Chen et al. 2022).

We analyzed the direction of patent diffusion between countries. Among the top 10 countries with most patents,



**Fig. 4** Patent right index (PRI) between 1970 and 2022, with positive values (red shades) indicating net-exporting countries (i.e., higher patent export than import) and negative values (blue shades) indicating net-importing countries. PRI is the ratio of the difference of

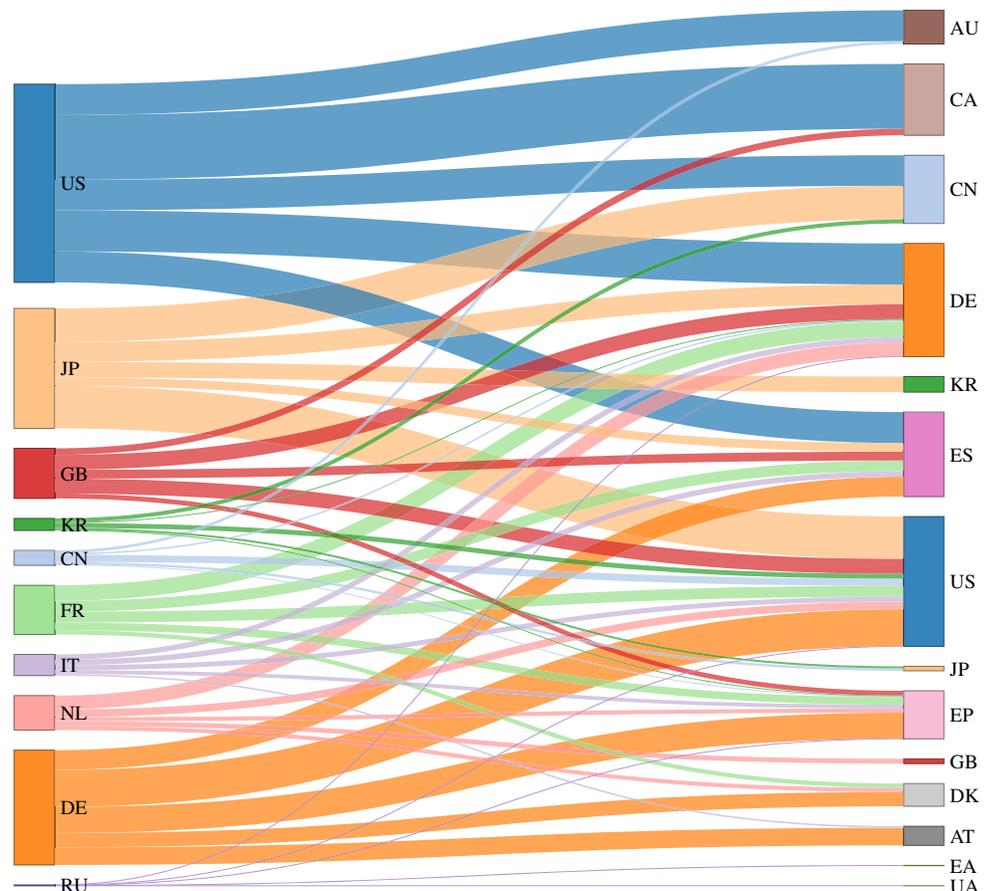
patent export and import in a given country (export–import) divided by the volume of patent exports of the country that exports the most patents.

only 2% of Russian patents were granted abroad, primarily in the Eurasian Patent Organization (EA), Ukraine, the US, and Europe (Fig. 5). The low ratio of abroad patent registration in Russia was in stark contrast to its role as a main crop exporter (Paulson et al. 2022), as 90% of product exports from Russia were raw materials and slightly-processed goods (Gulin et al. 2018). Similarly, only 2% of Chinese patents were granted abroad, primarily in the US, Australia, Japan, and Europe (Fig. 4), which agreed with previous research that most of the Chinese companies do not register patents abroad (Liu et al. 2014) and corresponded to the destinations of Chinese patent abroad filing in WIPO (World Intellectual Property Organization) report (Kashcheeva et al. 2014). In contrast, 83% of Japanese patents were granted abroad, mainly in the US, Asia, and Europe (Fig. 5), which might be due to the support measures of the Japan Patent Office (JPO) for medium-sized enterprises and universities who registered patents abroad (Japan Patent Office (JPO) 2010). The abroad destination of patent diffusion in European countries (the UK, Italy, the Netherlands, France, and Germany) were mainly in the US (Fig. 5), which agreed with the high-tech trade reports in 2022 that the United States was the EU's main partner for high-tech exports (Eurostat 2023).

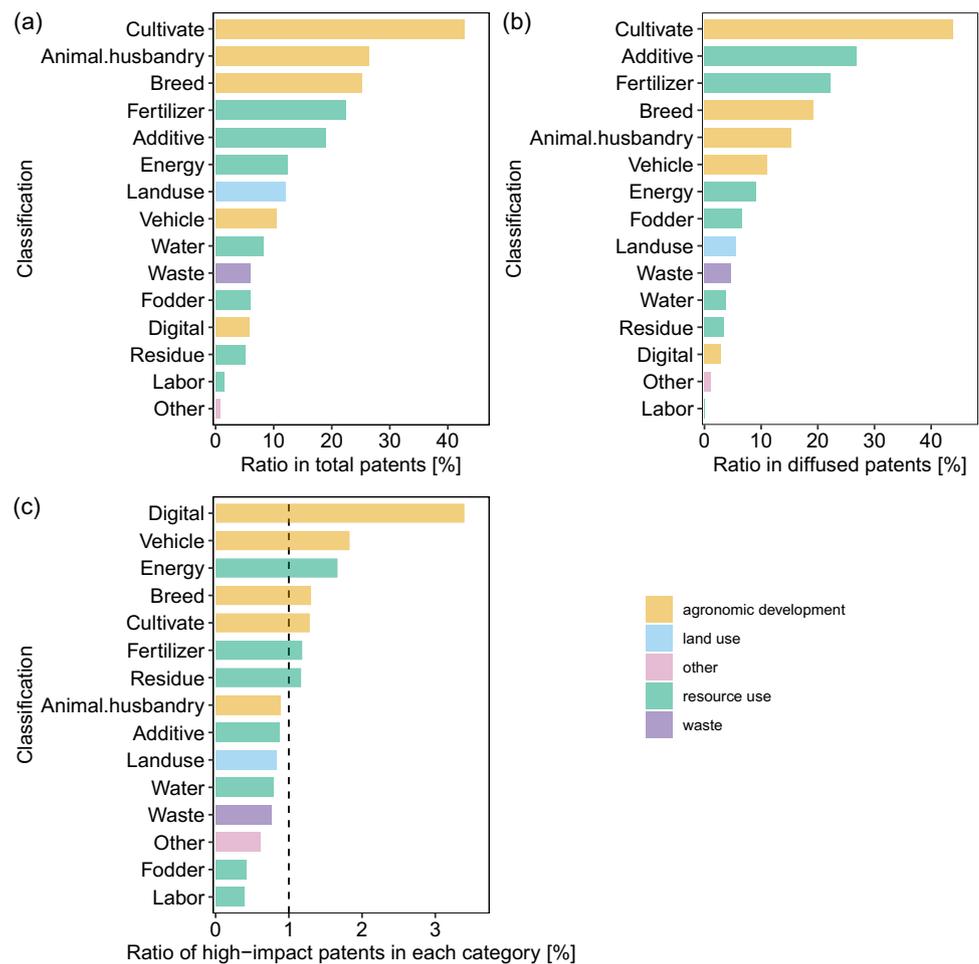
### 3.2 Agricultural patents related to different agricultural action fields and sustainable intensification

Among the different categories of agricultural patents (see patent examples for each category in Table S1), agronomic development and resource use were the primary foci of agricultural technological innovation (Fig. 6). For instance, plant cultivation was the most common category overall (43% of all patents, Fig. 6a) and within diffused patents (44%, Fig. 6b). In contrast, digital technologies had the highest ratio of high-impact patents (3%, Fig. 6c), despite making up only 6% of total patents (Fig. 6a) and 3% of the diffused patents (Fig. 6b). Among the different agricultural action fields, breeding, plant cultivation, and fertilizer are the foci of patent issuance, patent diffusion, and high-impact patents (Fig. 6), which agrees well with the primary foci of Chinese green patents on seed breeding, planting, and organic fertilizers (Hu and Xu 2022). Patents related to each agricultural category showed varied temporal trends and spatial variability in relation to patent numbers and diffused patents (Fig. S2). Patents mainly focused on animal husbandry and cultivation in China, and cultivation in Europe (Fig. 7). In North America and Australia, there had been a proliferation

**Fig. 5** Dominant diffusion directions of patents in the top 10 countries with most patent priority numbers during 1970–2022. Country codes are listed on European Patent Office (EPO) website: <https://register.epo.org/help?lng=en&topic=countrycodes>.



**Fig. 6** Ratio of each patent category in **a** total patents and **b** diffused patents and **c** ratio of high-impact patents in each patent category.



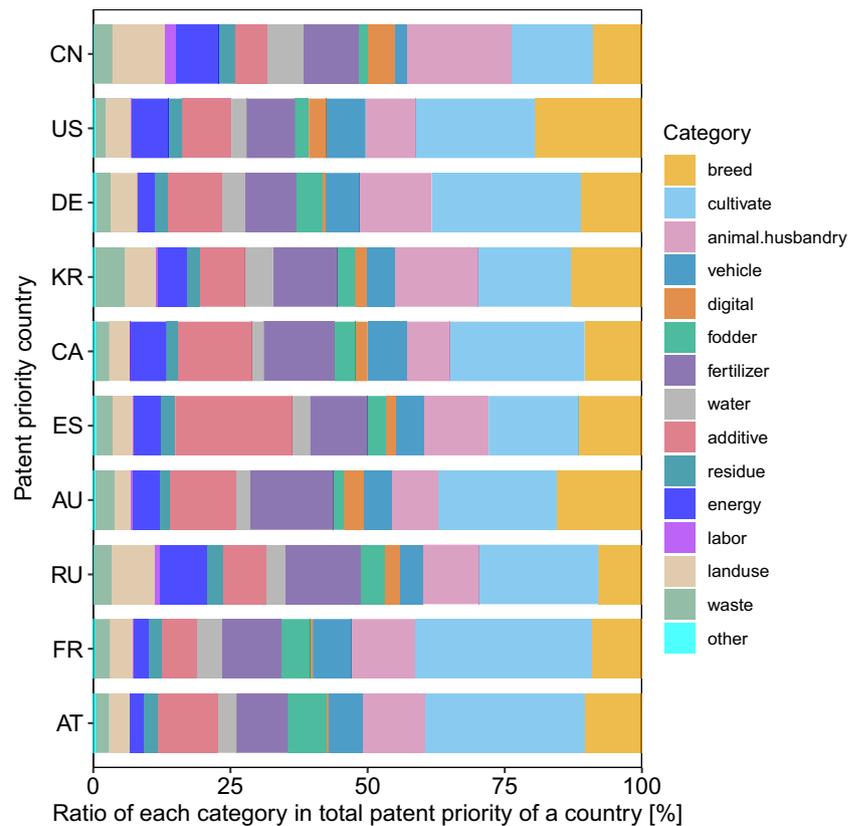
of breeding-related patents (Fig. 7), and this coincided with the widespread cultivation of biotech crops in these regions (James 2011). The low proportion of breeding patents in European countries coincided with the debate and low cultivation rate of biotech crops in Europe (Evenson and Gollin 2003; James 2011; Qaim 2020). In particular, additives were the main focus of Spanish patents, corresponding to the report that Spain was one of the countries with the highest levels of pesticide application in Europe (Rousis et al. 2017).

Over the five decades in this study, patents increasingly focused on efficiency and environmental friendliness, with more patents on average focusing on efficiency (24%) compared to environmental friendliness (11%), and thus an average of 4% of total patents focusing on both targets (Fig. 8a). Despite the overall low prevalence of SI targets in agricultural patents, SI-related patents had been increasing to 8% in recent years (Fig. 8a). This corresponds with the increased attention to SI in academic literature and the public consciousness since the 2010s (Weltin et al. 2018). However, in line with the overall patent trends, there had been a decrease in diffusion ratios for SI-related patents (Fig. 8b). This is particularly so since 2010s, with efficiency-related

patents considerably outnumbering environmental friendliness-related patents (Fig. 8a), but having a slightly lower PDR (24%) compared to the environmental friendliness patents (27%) (Fig. 8b). This suggests a potentially higher market potential of environmental friendliness-related patents than efficiency-related patents. The PDR of patents relating to both targets (i.e., SI) was only 14% (Fig. 8b), indicating that the majority of diffused patents focused on environmental friendliness only or efficiency only.

China led the patent priority related to efficiency (50%), environmental friendliness (40%), and SI (66%) targets, followed by the US (Fig. 8c). However, when considering only abroad-granted patents (patent diffusion), the US led the diffused patents (Fig. 8d) related to efficiency (33% in total patents), environmental friendliness (29%), and SI (29%) targets. Among the different categories of agricultural patents, patents related to energy (77% in SI-related patents), cultivation (55%), fertilizers (32%), and animal husbandry (30%) mainly supported the SI target (Fig. 8e). The contributions of each category supporting efficiency and environmental friendliness targets are shown in Fig. S3. With regard to the four agricultural action fields, agronomic development

**Fig. 7** The ratio of each patent category (indicated in different colors) in the total patent priority of a country. Country codes are listed on European Patent Office (EPO) website: <https://register.epo.org/help?lng=en&topic=countrycodes>.



and resource use patents contributed to 42% and 45% of the SI-related patents (Fig. 8e). This was in accordance with the review of Weltin et al. (2018), which found that the most common topics in SI-related literature are agronomic development (36%), resource use (29%), regional integration (26%), and land use allocation (9%).

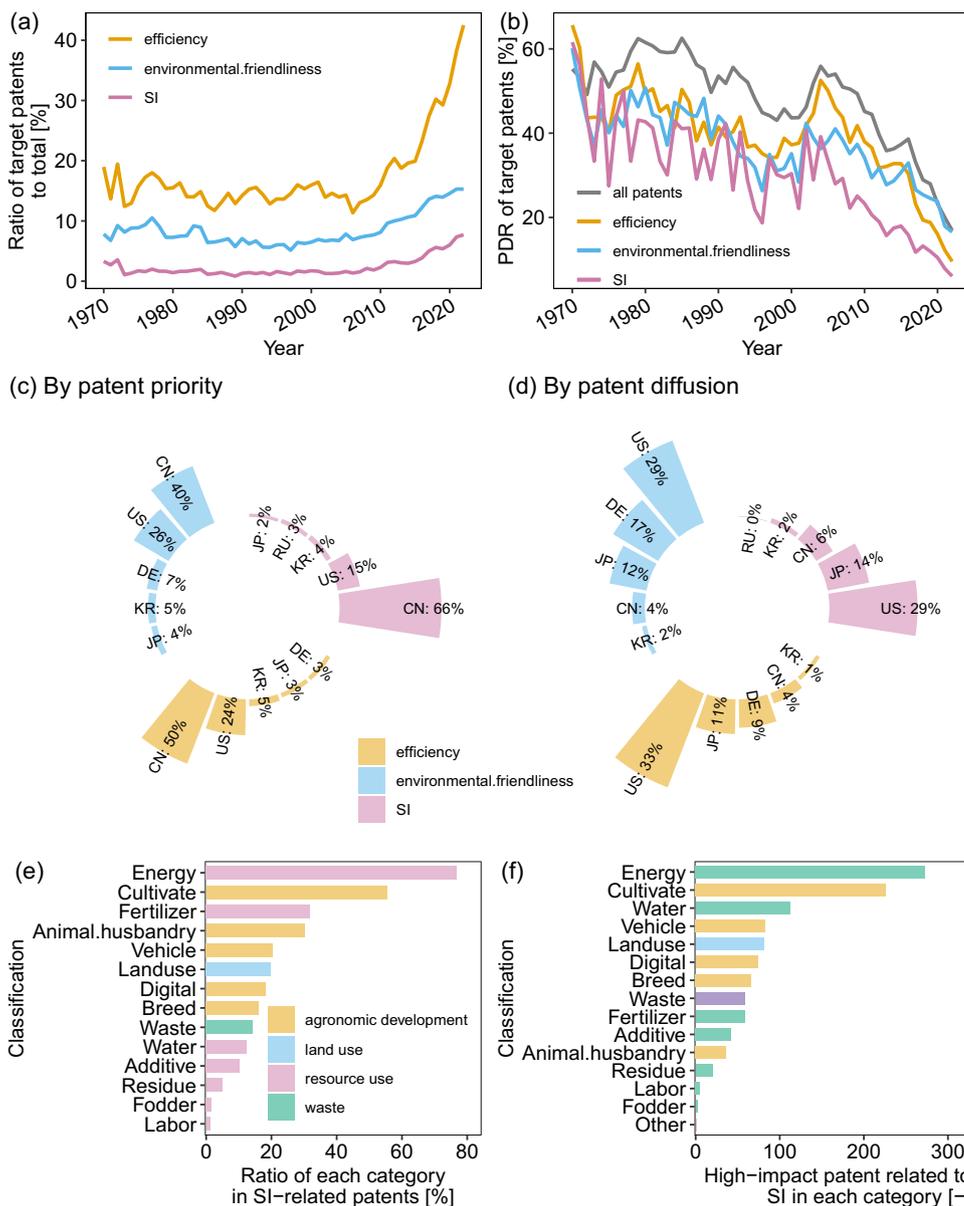
### 3.3 High-impact patents that related to sustainable intensification

Of the 6657 high-impact patents, 408 (6%) are related to SI. The SI-related high-impact patents were led by the categories of energy, plant cultivation, water, land use (mainly greenhouse), digital technologies, and breeding (Fig. 8f), with a high overlap of different agricultural action fields (Fig. S4). Besides, these high-impact patents in different agricultural categories have different impact levels as indicated in their citation curves (Fig. S5).

The representative high-impact SI-related patents listed in Table 3 summarized the leading functions of technologies, but may not cover all agricultural classifications to which these technologies belong (Fig. S4). Over the five decades in this study, SI-related patents describe progressively more diverse high-impact technologies (Table 3). High-impact cultivator and harvester patents with electric and pneumatic drivers had been supporting SI from the 1970s and became

more functional in allowing automation, variable-rate (VR) application, reduced and no tillage with residue use, and foldable header as well as yield estimation (Table 3). SI was supported by high-impact patents on technologies such as clean energy generators, waste energy recycling, and improved energy efficiency from the 1980s (Table 3). High-impact vehicle technology patents that support SI related to innovations in automation, steering systems, speed control, navigation, electric drivers, energy-saving, and recently in time management from 1980s (Table 3). High-impact digital technology patents related to SI have evolved from simple sensors in the 1980s to information and computer networking technologies in the current era (Table 3). SI-related pest/disease control was supported by high-impact patented technologies of genetic weed/pest control, mechanical pest killing, and nanopesticides in the 2010s and has innovated into autonomous ultrasonic pest repelling as well as the detection and forecast of pests and disease in recent years (Table 3). SI of greenhouses was supported by high-impact patents for greenhouse irradiation, environmental monitoring and control, and cultivation methods from the 1980s (Table 3). Most recently, high-impact patents related to SI have started to focus more on agroecology in ecological restoration, sustainable agricultural cycles, and diverse and organic fertilizer technologies, as well as resource-saving, clean-energy-driven, and intelligent applicators for water

**Fig. 8** Patents related to the targets of efficiency, environmental friendliness, and sustainable intensification (SI) between 1970 and 2022. **a** Ratio of target-related patents in total annual patents and the average ratios of target-related patents in total patents. **b** Annual patent diffusion rate (PDR) of target-related patents, as compared to PDR of all agricultural patents. **c, d** Ratios of target patents to patent priority and diffused patents in top five countries with most target-related patents. Country codes are listed on EPO website: <https://register.epo.org/help?lng=en&topic=countrycodes>. **e** Contribution of each patent classification to the high-impact patents related to SI. **f** SI-related high-impact patents in each classification of agricultural action fields. Country codes are listed on European Patent Office (EPO) website: <https://register.epo.org/help?lng=en&topic=countrycodes>.



and additives (Table 3). High-impact autonomous animal feeding and animal behavior control has been developed in supporting SI in recent years (Table 3).

High-impact patented technologies that supported SI were led by the technologies of renewable-energy-powered and resource-saving machines; digitalization supported by computer networking, information, and mapping; and agroecology and organic cultivation methods (intercrops, no tillage, residue use, and organic fertilizer among others), as well as genetic, mechanical, and ultrasonic methods for weed/pest/disease control (Table 3). Daum (2021) envisioned the future development direction of autonomous farming as aligning with either agroecological farming supported by small robots (i.e., utopia), or monoculture supported by large robots (i.e., dystopia).

In the prospects of ecological utopia, renewable-energy-powered robots would play a key role in supporting agroecological practices (Daum 2021). Renewable energy can reduce the dependency on fossil fuels (Davidson 2019), but the current effect of using non-fossil energy to displace fossil energy is still far from satisfactory (York and Bell 2019). Furthermore, many clean energy technologies are still in the prototype or demonstration phase (European Patent Office (EPO) 2021). The algorithms related to the safety, stability, and compatibility of agricultural automation still need to be improved (Jha et al. 2019; Salimi et al. 2020; Shutske 2023). The research and development in the integration of renewable energy and robot technologies are expected to stimulate advances in renewable-energy-powered robots (Iqbal and Khan 2017).

**Table 3** Decadal high-impact technologies that are related to agricultural sustainable intensification (SI). The values in parentheses indicate the corresponding numbers of patents. One patent may include different technologies, so the sum of values in the brackets can be more than the total numbers of high-impact SI-patents. Technolo-

gies belonging to different agricultural action fields are highly overlapping (Fig. S5). The representative high-impact SI-related patents listed here summarize the leading functions of technologies, but may not cover all agricultural classifications to which these technologies belong (Fig. S4).

Decade	High-impact technologies that relate to sustainable intensification (SI)
1970–1979	<ul style="list-style-type: none"> <li>•Applicator (3): additive sprayer, autonomous irrigation</li> <li>•Cultivator/harvester (1): multifunctional</li> <li>•Other minor technologies (1)</li> </ul>
1980–1989	<ul style="list-style-type: none"> <li>•Cultivator/harvester (25): autonomous, multifunctional, pneumatic, path regulating, reduced tillage</li> <li>•Waste energy (8) recycle technology</li> <li>•Greenhouse (5): cultivation method, environment monitor, irradiation</li> <li>•Vehicle (4): autonomous</li> <li>•Digital (3): grain sensor</li> <li>•Air purification (2)</li> <li>•Animal husbandry (2): additive, animal behavior control</li> <li>•Other minor technologies (5)</li> </ul>
1990–1999	<ul style="list-style-type: none"> <li>•Cultivator/harvester (6): electric, control system</li> <li>•Applicator (4): pneumatic additive applicator, autonomous irrigation</li> <li>•Vehicle (4): autonomous, steering system, speed control, energy saving</li> <li>•Fermentation (3)</li> <li>•Fertilizer (2): compost</li> <li>•Greenhouse (2): irradiation</li> <li>•Energy generator (2): solar, electric</li> <li>•Other minor technologies (4)</li> </ul>
2000–2009	<ul style="list-style-type: none"> <li>•Cultivator/harvester (19): electric, pneumatic, multifunctional, variable-rate (VR)</li> <li>•Vehicle (17): autonomous, steering system, navigation, energy-saving, electric</li> <li>•Digital (5): information transmission, mapping, sensor, signal identify</li> <li>•Biodegradable packing (4)</li> <li>•Air purification (2)</li> <li>•Applicator (2): autonomous irrigation, irrigation controller schedule</li> <li>•Energy generator (2)</li> <li>•Greenhouse (2): irradiation, environmental control</li> <li>•Other minor technologies (5)</li> </ul>
2010–2019	<ul style="list-style-type: none"> <li>•Cultivator/harvester (13): autonomous, path regulating, no tillage</li> <li>•Vehicle (11): steering, navigation, automation, electric</li> <li>•Energy generator (8)</li> <li>•Waste energy recycle technologies (8)</li> <li>•Pest control (8): genetic weed/pest control, mechanical pest killing, nanopesticide</li> <li>•Digital (7): autonomous cleaning, autonomous micro-irrigation, sensor, mapping, variable rate (VR)</li> <li>•Greenhouse (3): irradiation, environmental monitor</li> <li>•Other minor technologies (5)</li> </ul>
2020–2022	<ul style="list-style-type: none"> <li>•Cultivator/harvester (52): pneumatic, electric, autonomous, path regulating, foldable header, yield estimation, multifunctional, reduced tillage and residue use, variable rate (VR)</li> <li>•Agroecology (34): ecological restoration; ecological aquaculture; rice-fish system</li> <li>•Applicator (23): water-saving, drip, autonomous, wind-power and rainwater-collection irrigation; pneumatic, resource-saving, autonomous additive applicator</li> <li>•Energy generator (17): portable power supply; wind, photovoltaic energy generator</li> <li>•Fertilizer (14): from manure, household garbage, sludge, algae</li> <li>•Digital (13): network, information transmission, mapping, sensor</li> <li>•Greenhouse (13): irradiation, cultivation, and environment monitor</li> <li>•Weed/pest/disease control (12): autonomous detection/forecast; mechanical pest killing, ultrasonic pest repelling</li> <li>•Animal husbandry (10): autonomous feeding; animal behavior control</li> <li>•Crop processing (10): autonomous vegetable cleaning</li> <li>•Vehicle (7): autonomous, steering system, navigation, time management</li> <li>•Cultivation method (6): intercropping, mulching</li> <li>•Waste treatment (6): wastewater treatment, water recycle, CO<sub>2</sub> utilization, nutrient recycle</li> <li>•Other minor technologies (8)</li> </ul>

Weed, pest, and disease control has been developed in the directions of mechanical pest killing, ultrasonic pest repelling, and genetics, as well as autonomous detection and forecast models (Table 3). Apart from increasing crop yield, genetically modified (GM) crops are expected to help improve the tolerance to pesticide and abiotic stresses and the resistance of crops against pests and diseases (Chavas et al. 2014; Kim et al. 2018; Jiang 2020; Kumar et al. 2020). However, GM crops raise concerns about the nutritional qualities of food (Napier et al. 2019), public acceptance (Kim et al. 2018), and autonomy of farmers (Deichmann et al. 2016; Sanders 2022), as well as legal and regulatory issues (Kerr and Newell 2003; Peschard 2014; Qaim 2020). The non-transgenic method by genome editing of crops can be an alternative breeding technology for weed/pest/disease control (Georges and Ray 2017; Möhring et al. 2020).

Despite making up lower proportions of the total agricultural patents, digital technologies were found to be the focal point of high-impact patents in supporting SI, especially in the recent past (Fig. 6e; Table 3). Digital technologies can increase farm efficiency, reduce the use of agrochemicals, and improve farmers' decision-making capacity (Lioutas et al. 2021). Digitalization can integrate the modules of improving operational and resource use efficiency and Internet of Things (IoT) and create transparent marketplaces among others (Brody and Pureswaran 2015; Small 2017; Finger et al. 2019; Dayioğlu and Turker 2021). However, the promotion of digitalization is thought to be a challenge for small-scale farmers, low-skilled farm workers, and poorer countries (Lioutas et al. 2021). Some research argued that digital technologies can overcome the information access challenges of small-farm holders by providing free platform services and improving agricultural supply chain management (Deichmann et al. 2016; Sanders 2022). Therefore, despite the promising prognoses of digital technology in supporting SI, the actual promotion of these technologies is subject to farmers' economic situation and knowledge, as well as market transparency (Deichmann et al. 2016; Lioutas et al. 2021; Sanders 2022). During a transition period, and in countries where the training levels of farmers lack specialized knowledge of agricultural technologies, service providers may be first adopters of those technologies and may use them on farmland when commissioned by farmers.

### 3.4 Limits of using patents to understand global agricultural innovation and research avenues

Our analysis of more than one million patents has provided a comprehensive overview of the main patterns and trends of agricultural innovation over the past 50 years. Our methodology enabled us to compare patents across countries and among agricultural action fields, over time, to an extent not reached by previous analyses. Yet the broad, exploratory

nature of our analysis inevitably has limitations that merit discussing.

#### 3.4.1 Keyword analysis

We note that due to the large sample size, there are inevitable inaccuracies in our results (e.g., some mis-classifications). Our agricultural patent dataset was based on the searching of keywords in CPC titles (Fig. 2). The approach enabled us to capture non-English patents and exclude non-agricultural patents. However, we might have missed a small number of patents that were not included in the selected classifications, which might have induced some underestimation of patents in each category. Especially, patents with unspecific titles and missing abstracts, as well as the translation of non-English patents, might have increased the uncertainty of our classification. Our keywords used for the classification of efficiency and environmental friendliness-related patents were limited based on patent keyword analysis and the existing expertise among the authors, which might have led to an underestimation of the ratio of SI-related patents. For instance, SI-level in agricultural patents might be underestimated, because the keyword list of "environmental-friendliness" targets excluded "biological" (6% of total patents), which covered both SI-related (e.g., "biological pest control") and SI-irrelevant patents (e.g., "biological processes of animal gene editing"). Adding "biological" to the set of "environmental-friendliness" keywords would increase the SI proportion to 6%, but would also include some non-SI patents.

#### 3.4.2 Patent indicators

We used patent diffusion and patent citation as the indication of technology potential. However, these indicators have limitations:

1. Besides patenting, trademarks and copyrights can also protect technology innovation (United States Patent and Trademark Office (USPTO) 2021). Other approaches to technology innovation such as technology designed by farmers might not be registered for protecting intellectual property rights (FarmHack 2013). These make it hard to have a comprehensive and integrated summary on technology innovation.
2. We used the number of patent citations as an indication of patent market values and innovation levels (Owen-Smith and Powell 2003; Hall et al. 2005; Park et al. 2023). However, Bessen (2008) argued that citation statistics rather represent the value of the underlying technology than the value of the patent itself. The following two aspects can explain the difference between technology value and patent value (Bessen 2008; Nurbatsin

2020): (a) Inventors can create appropriate value from technologies by non-patent measures of leading-time advantage and trade secrecy; (b) patent applicants may expend efforts to add more citations in their patent drafts for insulating the patent from possible prior art (i.e., a concept in patent law used to determine the patentability of an invention). Also, given the huge diversity of technologies represented in the patent database, it may be difficult in reality to equally consider their diffusion processes (e.g., “robots” versus “waste management processes”), as the technologies relate to distinct components of the agricultural production system.

3. Technology transfer and adoption can be affected by social, economic, and political factors in different ways. For instance, lacking public acceptance of GM crops limits the adoption of breeding technology (Lucht 2015). However, pesticide bans and worries about pesticide residues on crops and in the environment may promote the adoption and acceptance of genome editing crops (Georges and Ray 2017; Möhring et al. 2020). Despite these limitations, we found spatial coincides between breeding-focused patents and biotech crop cultivation (Evenson and Gollin 2003; James 2011; Qaim 2020) and between top patenting countries and leading countries in global food and agricultural network (Veeck et al 2020).

### 3.4.3 Technology invention, transfer, and adoption

Overall, technology as one of the pathways towards agricultural SI appears to be increasingly prevalent in patents (i.e., technology innovation). However, there remain challenges and questions about market transfer and farm adoption, assessing and solving potential negative impacts, public acceptance (Kim et al. 2018; Lucht 2015), policy and law constraints (Ehlers et al. 2021; Freeman and Freeland 2014), knowledge popularization (Shikuku 2019), and transparent marketplaces (Brody and Pureswaran 2015). Our study informs about the potential “offer” of future technologies, but not about their acceptance and actual uptake.

Technological innovation needs to be complemented by social innovations in landscape management, policy making, and regional integration, as well as non-technological cultivation management (Vanlauwe et al. 2014; Petersen and Snapp 2015; Chavarría et al. 2018; Weltin et al. 2018; Williams et al. 2023). For instance, the conflicts of pesticide control and reduced tillage can be mediated by crop rotation, cover crops, intercrops, and green manure crops (Hunt et al. 2017; Melander et al. 2020; Pekrun et al. 2023). Moreover, organic-source fertilizer and animal husbandry technologies need to be supported by farm structure management to reach the regional cycling of crop-livestock systems (Bayram et al. 2023). In contrast, biodiversity is less supported by technology, but rather by crop rotation, flower strips, and hedgerows (Armengot et al. 2015; Albrecht et al.

2020), which all need government and institutional support to cope with complex regional conditions and provide the efficacy of SI measures and land-use planning for agroecological zoning (Armitage et al. 2012; Zasada et al. 2017; Weltin et al. 2018). Our patent analysis thus relates most closely to the “efficiency” form of SI and must be complemented by other forms of substitution and system redesign (Haughey et al. 2023).

## 4 Conclusions

To the best of our knowledge, this study is the first comprehensive analysis of the one million agricultural patents issued worldwide in the last five decades, detailing the temporal trends and spatial distributions of patent origins, geographic spread, related agricultural action fields, and high-impact patent evolution. Based on our results, we make the following recommendations for future research and policy.

First, technological innovation needs to place greater emphasis on sustainability. While the share of SI-related patents has increased over time, only 8% of agricultural patents in recent years have related to both efficiency and environmental friendliness. Among these objectives, considerations of efficiency far outnumber those of environmental friendliness. For technologies to play a greater role in SI of agriculture, they therefore need to be more emphasized on SI in government- and industry-supported research and development.

Second, more research is needed to better understand the relationships between technological innovation and SI impacts. Whether patented technologies will be transferred into marketed products and actual spread depends on economic, regulatory, and societal factors, as well as on farmers’ attitudes. Our study provides a comprehensive overview of the theoretical availability of SI-related technologies, including how these have evolved over time. However, this needs to be complemented by case study research to understand how patents propagate (or not) to impact technology adoption and agricultural sustainability outcomes.

SI does not necessarily depend on a single new technology, but existing and new technologies have to be combined to this end. Patents also only inform about technologies that may become available on the market, but do not cover technologies protected by trademarks and copyrights, as well as technologies designed by farmers that directly enter the public domain. SI is a multifaceted goal that also implies land-use decisions at farm, regional, and supra-regional scale, supported by technology, policy making, and institutional research.

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**Data availability** The datasets are available from the corresponding author on reasonable request.

**Code availability** Data downloads were performed with Jupyter Notebook (Kluyver et al. 2016). Analyses were conducted with R (R Core Team, 2022). The specific packages are mentioned in the “Methods” section. Custom code is available from the corresponding author on reasonable request.

## Declarations

**Conflict of interest** The authors declare no competing interests.

**Ethics approval** This study does not need ethical approval.

**Consent to participate** This study does not need participating consent.

**Consent for publication** This study does not need publication consent.

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