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Meta-analysis of intellectual property and commercialization practices in seed and planting material systems

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ABSTRACT

Seed constitutes a fundamental component of agricultural growth and plays a crucial role in ensuring the prosperity of the farming sector. To maintain the supply of such seed in the market, and to safeguard its IP protection is the key responsibility of crop-based research and policy stakeholders. The results of this study revealed that China (41.95%) is the leading country in registering its plant varieties followed by the European Union, Japan, Netherlands, Russian Federation, and Asia is the leading continent (51.48%) at UPOV. India's PPV&FR Authority has received plant varieties of 160 crop type for registration, out of these rice (*Oryza sativa* L.) is the leading crop with 36.11% of the overall submission of the varieties and 45.20% of the total certificate issued; followed by maize (*Zea mays* L.), *tetraploid cotton*, pearl millet, wheat (*Triticum aestirum* L.) and others. Technology commercialization efforts by Indian Council of Agricultural Research successfully transferred 462 varieties of its 85 crop species through agreements with 959 public and private organizations and individual entrepreneurs. The pan India reach of ICAR's basket of improved seed and planting material innovations is sufficient enough to justify the Councils' role in enabling farmers for better harvest, livelihood and food security. The worldwide seed business is regionally centralised in the European Union, USA, and South-east Asia. Cereal and vegetable varieties are leading the research as well as IP protection in India and abroad equally.

Keywords: Commercialization, Innovation, Patent, Plant variety, PPV&FRA, UPOV

Seeds are the fundamental unit for crop-based research, production, improvement and policy development. Quality of the seed is a critical component of national and international food policy, research agendas, human health and nutrition, agricultural industrialization, and livestock production. Ensuring the production and management of high-quality seeds is the shared responsibility of public and private crop research institutions, supply chain agencies, policy makers, funding organizations, and farmers.

To sustain the seed research and production, for maintaining both quality and quantity to meet growers' demand and global food supply needs, the first major initiative began in 1924 with the 'First International Seed Congress' in London. This led to the establishment of Federation Internationale du Commerce des Semences (FIS) and International Seed Testing Association (ISTA). Later, in 1938, the International Association of Plant Breeders for the Protection of Plant Varieties (ASSINSEL) was formed to establish a system for protecting plant breeders' rights (Dadlani *et al.* 2025).

The FIS further advanced its efforts by revising 'Rules and Usages for the Trade in Seeds for Sowing Purposes' in 1950. This was followed by adoption of the International Plant Protection Convention (IPPC) in 1951. Subsequently, the 'First International Conference for the Protection of Plant Varieties' (1957) paved the way for adoption of First Act of the 'International Union for the Protection of New Varieties of Plants (UPOV) Convention' (1961) and its revised version in 1991. An important amendment in 1978 introduced the provision for farmers' privilege, while also imposing certain restrictions on Plant Breeders' Rights (PBRs) (Dadlani *et al.* 2025).

The World Trade Organization's (WTO) Agreement on 'Trade-Related Aspects of Intellectual Property Rights (TRIPs)' (1995) mandated protections for plant varieties, creating the framework for the subsequent adoption of 'International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGFRA)' in 2001 (Dhillon and Agrawal 2004). Under TRIPs provisions, all signatory nations are

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required to implement PBRs through either patent systems or a *sui generis* protection (Brahmi *et al.* 2022). These requirements directly influenced India's establishment of a farmers' rights framework, culminating in the enactment of 'Protection of Plant Varieties and Farmers' Rights (PPV&FR) Act' in 2001 (https://plantauthority.gov.in/).

To consolidate nearly eight decades of institutional progress, the 'International Seed Federation (ISF)' was formed in 2002 through the merger of FIS and ASSINEL, now serving as a single window international organization for the advancement and protection of plant genetic resources (PGR). The ISF is a non-governmental, non-profit organization that advocates for the global seed industry, promoting the free movement of seeds within a framework of science-based equitable regulations. As the leading voice for seed sector interests, ISF collaborates with major international organizations including OECD (Organization for Economic Cooperation and Development), UPOV, IPPC, FAO (Food and Agriculture Organization) and CBD (Convention on Biological Diversity) (https://worldseed.org/).

The transformative potential of quality seeds (possessing traits that enhance crop performance) was first demonstrated through hybrid maize production in the United States of America (USA) and further reinforced by subsequent advancements (Dadlani *et al.* 2025). Recognizing the pivotal role of Intellectual Property (IP) and PBRs in seed research and development, there is increasing emphasis on understanding their effective management and transfer mechanisms to end-users. As India's premier agricultural research institution, the ICAR has systematically addressed these needs by establishing a three-tier IP management and technology commercialization system in 2006–07. This initiative serves the dual purpose of compliance with TRIPs agreement requirements, and fostering a robust agri-business ecosystem. This system operates through continuous engagement in IP protection and management, technology commercialization/licensing, agri-business and start-up incubation.

A cornerstone of this initiative is the National Agriculture Innovation Fund (NAIF), under which the current study was conducted by ICAR's Intellectual Property and Technology Management Unit (IP&TM). The present study aims to conduct the meta-analysis of current status of Indian seed sector, seed import and export, plant variety protection mechanisms at both national (PPV&FRA) and international (UPOV and Patent Filing Offices) levels, patent filing trends in crop-based research institutes and universities, and the technology transfer mechanisms for both protected and non-protected seeds and planting materials. The goal is to comprehensively know about how IP management and technology commercialization initiatives contribute to agricultural innovation and sectoral development, thereby facilitating future policy and institutional strategies.

The study focused on assessing plant variety, and patent protection mechanisms and the pathways through which protected varieties are transferred to the end users via commercialization. To achieve the stated objectives primary and secondary data sources were used from relevant public and private organizations. Relevant software tools and search engines were employed to collect, organize, and analyse the data. The methodological framework included the following components:

Indian seed sector: To provide a continuity to the discussion, data and review supporting historical background of the Indian seed sector is described to connect the study with ongoing initiatives.

Import and export of seed: There are significant variations in global seed trade patterns across different crop categories, with certain countries specializing as top exporters or importers depending on the crop type (International Seed Federation 2025a, b). To get the seed trade patterns, ISF trade report of 2022 covering seed export data from 74 countries and import data from 116 countries were accessed for this meta-analysis. To support these datasets ISFs' earlier reports (from 2014 onwards) were also used and compared.

Plant variety database: To assess trends in plant variety protection at both national and international levels, data was sourced from PPV&FRA, Seednet India Portal and UPOV databases. Recent publications and official websites of these organizations were accessed to ensure data relevance and accuracy. The databases were used from these agencies are duly updated up to March 2025.

Patent database: Patent filing trends from crop-based research institutes of ICAR were analysed using the Indian Patent Office (IPO) database. To evaluate global patenting trends in major staple food crops, the Questel Orbit patent search engine was utilised to access last 20 years data on 25 key crop species from 2006–2025. Patents were analysed in five major parameters, namely, year of filing, legal status of the filed patent applications at different Patent Filing Offices (PFOs), major research areas, top five applicant organizations and top filing countries. Special emphasis was placed on patent claims, considered the core of a patent document, as they define the scope and strength of the innovation. Accordingly, keyword searches were performed using the names of selected crop species, and only those patents that included the crop names in their claims were selected for further analysis.

Top-100 agricultural universities: To explore academic contributions to agricultural IP generation, the top 100 agricultural universities were identified using Research.com, a leading educational platform (https://research.com/university). The 3rd edition of Research.com rankings in agriculture science was based on data consolidated from a wide range of data sources including OpenAlex and CrossRef. Citation-based metrics were calculated using bibliometric data collected on 21 November 2023. Rankings were determined by the aggregate Discipline h-index (D-index) of affiliated scholars at each institution, which reflects both publication output and citation impact in the field of agricultural sciences.

The above-mentioned plant variety and patent filing

trends with import and export data will be analysed to get the overall scenario of seed production and its market in India and abroad.

Technology commercialization: Trends in the commercialization and licensing of plant varieties within the National Agricultural Research and Education System (NARES) were assessed through a review of ICAR Annual Reports spanning 2007 to 2024. These reports provided data on technology transfer activities.

Study period: The data collection, analysis and writing work completed in between July, 2024 to March, 2025.

Data analysis: The compiled data and literature were analysed using appropriate statistical tools. The results were organized and presented under key thematic areas, namely, Indian Seed Sector, Seed Business Scenario, Plant Variety Protection at UPOV, Plant Variety Protection at PPV&FRA, Seednet India Portal insights, Patent Filing Trends in ICAR Crop-Based Research Institutions, Patent Filing Trends at Top-100 Agricultural Universities, and Trends in Plant Variety Commercialization/Licensing at ICAR.

Literature review of this study revealed a limited number of comprehensive research studies, projects, or reports both nationally and internationally focused on the intellectual property (IP) protection and commercialization of seeds and planting materials. Most available documents were restricted to registration data, summary statistics, or organizational reports, indicating a significant gap in detailed academic research on the subject.

Indian seed sector: The research and policy supported breakthrough occurred in Indian seed sector during the Green Revolution, which served as a catalyst for the country's organized seed sector. This sector traces its origins to the late 18th century, following the Industrial Revolution in Europe, and initially involved the import of exotic vegetable seeds from the United Kingdom and continental Europe. Key milestones in its development include the establishment of Indian Agricultural Research Institute (IARI) at Pusa, Bihar (1905), and the Royal Commission's report to the government (1928).

The success of the Green Revolution propelled India's seed industry into becoming the world's fifth-largest seed market, valued at USD 6 billion, and renowned for its dynamic public-private integration (Dadlani *et al.* 2025). Globally, the USA dominates the seed market with a 35% share, followed by China (16%), France (9%), Brazil (8%), India (6%). Today, India's seed industry not only ensures reliable access to quality seed for its farmers, but also supports food security, providing 1.87 kg of food per person per day to world's largest population (Dadlani and Yadav 2022, Chand and Singh 2023).

In India, crop variety development is a continuous process under the All-India Co-ordinated Research Projects (AICRPs) and closely monitored by the National Agricultural Research and Education System (NARES) which comprises Indian Council of Agricultural Research (ICAR) institutes and State Agricultural Universities (SAUs). The newly developed varieties are first notified in the Gazette of India in

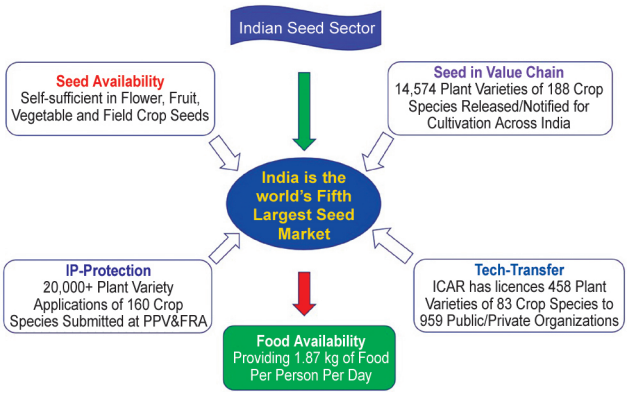

Fig. 1 IP and technology supported Indian seed scenario.

the guidance of Central Sub-Committee on Crop Standards, Notification and Release of Varieties for Agricultural Crops. Over the past decade (2014–2024), this system has produced 2,900 location-specific high-yielding field crop varieties, which have been integrated into the national seed distribution chain. To facilitate seed multiplication, 11.85 lakh quintals of breeder seed have been supplied to public and private sector seed agencies for its downstream production of foundation and certified seeds. Notably, over 70% of total seed supply consists of varieties developed within the last 10-years, reflecting a strong emphasis on modern, high-performance genetics.

To further enhance accessibility, the Ministry of Agriculture and Farmer's Welfare, Government of India has implemented the 'Seed Village Programme'. This initiative ensures the decentralized availability of seeds of climate resilient, bio fortified and high-yielding varieties directly to the farmers at the village level (PIB 2025a).

Over the past decade (2013–14 to 2023–24), these initiatives have demonstrated significant success, as evidenced by substantial productivity gains across major crops. This comprises total food grains (18.63%), rice (19.26%), wheat (13.16%), maize (25.22%), total pulses (15.47%), total oilseed (12.60%), sugarcane (11.96%), jute (5.46%) etc. These remarkable yield improvements have not only strengthened India's food security but also enhanced its capacity to meet domestic demand while maintaining export commitments (PIB 2025b). The overall scenario of Indian seed sector from research-based IP protected innovations to adequate availability of seed in value chain through public and private technology transfer leads to the surplus food availability (Fig. 1).

Global seed industry growth and India's emerging role in seed trade: Based on data from ISF for seed trade report of 2022 covering seed export data from 74 countries and import data from 116 countries, Table 1 provides details of the top five seed-exporting and -importing countries for five major crop categories (field crops, vegetable crops, flower seeds, potato seeds, and tree seeds).

According to the 2022 export data, India led in vegetable seeds, France led in field crop seed exports, and the Netherlands dominated flower, potato, and tree seed exports.

Other key exporters included Poland, USA, Germany, China, and the UK across various crop categories. On the import side, Belgium was the top importer of field and tree seeds, the Netherlands led in vegetable seeds, Canada in flower seeds, and Egypt in potato seeds. Other major importers included Italy, China, India, USA, and Germany across various crop types. In the same trend ISF has published eight such reports from 2014 onwards, which revealed the similar trends with minor changes in country rankings.

The global seed industry has experienced steady growth, recording a Compounded Annual Growth Rate (CAGR) of 4.5%, increasing from USD 52 billion in 2013–14 to USD 70 billion in 2023–24. India is emerging as a key player in this sector, with its seed industry valued at approximately USD 6 billion in 2024, and projections estimating it to reach USD 10 billion by 2034. However, India's share in global seed exports remains relatively low, accounting for only around 1% (USD 150 million), in sharp contrast to leading exporters such as the Netherlands (USD 3.2 billion), France (USD 2.3 billion), the United States (USD 1.8 billion), and Germany (USD 1.1 billion) (Dadlani *et al.* 2025).

In terms of worldwide trade, India is mainly self-sufficient in flowers, fruits, vegetables and field crop seeds. The global seed trade data exhibits distinct specialization patterns, with specific countries leading in different crop categories, reflecting strategic strengths and market focus. India has established itself as a major producer with robust domestic industry growth, particularly in vegetable seeds, and is an outcome of continuous efforts in research, policy and coordination. However, its contribution to global seed exports remains minimal (~1%), highlighting a critical gap between production capacity and international trade performance. This underscores the need for enhanced export-oriented strategies, international collaborations, and supportive policy frameworks to fully leverage India's growing seed sector on the global stage.

Plant variety protection at UPOV: The global seed business is fundamentally supported by crop improvement and plant variety development initiatives carried out by both public and private sector organizations. The International Union for the Protection of New Varieties of Plants (UPOV) is an intergovernmental organization established in 1961 under the International Convention for the Protection of New Varieties of Plants. Its primary objective is to provide and promote an effective system of plant variety protection (PVP) that encourages the development of new plant varieties for the benefit of society (UPOV 2025). Currently, UPOV has 80 member countries, all of which can submit plant variety applications through the UPOV platform. Membership began in 1968 with countries such as the United Kingdom, the Netherlands, Germany, and Denmark, and later expanded to include France (1971), the United States (1981), China (1999), the European Union (2005), and the African Intellectual Property Organization (2015). Most recently, Nigeria became the 80th member, joining in March 2025.

To analyse trends in plant variety filings at UPOV, data from the past eight years (2016–23) were compiled and examined using various UPOV reports and search tools. The analysis indicates that a total of 68 countries collectively filed 167,685 plant variety applications during this period (Table 2). Out of these, 127,549 (76.06%) titles were granted, while 52,208 applications were ceased due to non-compliance with registration criteria. As of 2023, there are 983,056 active titles in force under the UPOV system across member countries. Among the countries that filed plant variety applications at UPOV during 2016–2023, the Netherlands (3.78%), Russian Federation (3.76%), and other top-performing nations collectively accounted for 92.48% of all titles issued. China received the highest share of titles issued during this period (22.89%), followed by the United Kingdom (18.44%), European Union (18.27%), Japan (4.20%), and the Russian Federation (4.01%). Furthermore, 87.86% of the currently active titles (as of 2023) are held by these top 20 countries. Within this group, the European Union leads with the highest proportion of titles in force (30.92%), followed by Japan (11.67%), Netherlands (5.41%), China (5.11%), and Russian Federation (4.30%). This concentration of both issued and active titles among a small number of countries highlights their dominant role in global plant variety protection under the UPOV system.

Fig. 2 presents the continent-wise distribution of plant variety applications filed under the UPOV system. Europe leads in the number of countries with issued (53.53%)

Table 1 Top five seed exporting and importing countries in terms of seed quantity

Field crops		Vegetable crops		Flower seed		Potato seed		Tree seed	
Export	Import	Export	Import	Export	Import	Export	Import	Export	Import
France	Belgium	India	Netherlands	Netherlands	Canada	Netherlands	Egypt	Netherlands	Belgium
Poland	Italy	New Zealand	China	Germany	Germany	France	Belgium	China	USA
USA	Netherlands	Italy	India	China	Netherlands	United Kingdom	Italy	Slovakia	Italy
Slovakia	Spain	Netherlands	Canada	USA	USA	Germany	Spain	Hungary	China
Czechia	Germany	USA	USA	Denmark	United Kingdom	Canada	Germany	Belgium	Slovakia

Source: ISF (2025a, b)

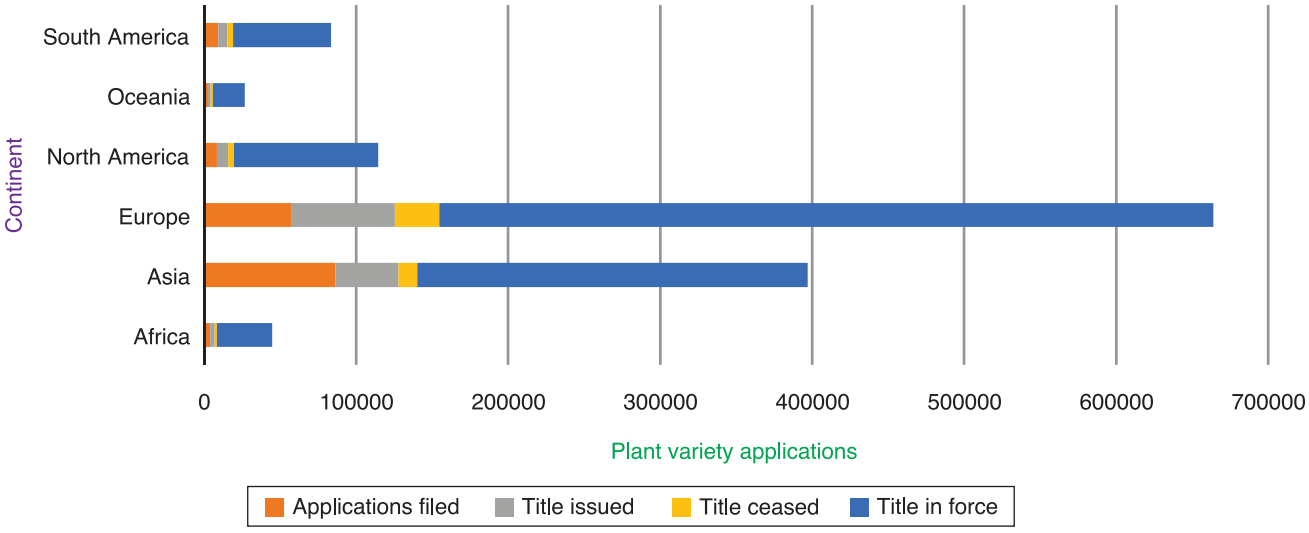

Fig. 2 Continent wise plant variety applications at UPOV (2016–2023).

Table 2 Top-20 country's plant variety filing trends at UPOV (2016–2023)

S No	Authority/ Country	Applications filed	Titles issued	Title ceased	Titles in force
1	China	70,348	29,195	2,673	1,29,032
2	European Union	26,766	23,303	16,145	2,26,268
3	Japan	6,461	5,363	6,094	64,653
4	Netherlands	6,339	5,097	2,828	72,244
5	Russian Federation	6,313	5,126	2,250	40,965
6	Ukraine	6,043	4,515	184	38,349
7	Republic of Korea	5,445	4,289	2,200	45,365
8	United Kingdom	3,812	23,520	778	31,982
9	United States of America	3,563	3,449	1,971	62,355
10	Argentina	3,026	950	821	19,389
11	Canada	2,781	1,815	1,399	15,589
12	Brazil	2,732	2,052	1,462	20,433
13	Australia	2,605	1,656	1,532	21,033
14	South Africa	2,307	1,955	987	26,294
15	Mexico	1,952	1,906	335	16,692
16	Viet Nam	1,649	739	378	4,114
17	Turkey	1,096	928	204	4,952
18	Poland	1,001	649	467	10,032
19	Colombia	1,001	659	401	5,359
20	France	902	794	1,131	8,640
	Grand total	1,56,142	1,17,960	44,240	8,63,740
	Overall applications (68 institutes)	1,67,685	1,27,549	52,208	9,83,056
	% share in overall filing	93.12	92.48	84.74	87.86

and active (51.81%) titles, with 36 member countries contributing to this share. In contrast, Asia is the leading region in terms of new plant variety applications, accounting for 51.48% of total filings during the analysed period, followed by Europe (34.05%). It is important to note that the United States database includes both plant variety protection certificates and plant variety patents.

As of the latest update, UPOV has registered 989 crop species under its plant variety protection system. To assess crop-wise application trends relevant to India's agricultural research priorities, 22 major crops were selected based on their alignment with the ICAR mandate. These include species across four broad crop groups: cereals (5), oilseeds (8), pulses (7), and cash crops (2). Among them, maize is the most frequently registered crop, with three species accounting for 174,687 titles, followed by wheat (6 species/143,032 titles), mustard (3 species/88,538 titles), barley (83,532 titles), sunflower (2 species/81,942 titles), and others. Detailed crop-wise statistics are presented in Table 3.

The trends observed in PVP registration in the UPOV are consistent with the global expansion of the seed industry, particularly across key seed-based economies such as the USA, China, France, Germany, the Netherlands, India, Italy, Japan, and the Russian Federation. These countries have played a significant role in both the development and protection of plant varieties under the UPOV framework. Although India is not a member of UPOV, it has complied with its obligations under the TRIPs Agreement by adopting a *sui generis* system, which led to the enactment of the Protection of Plant Varieties and Farmers' Rights (PPV&FR) Act in 2001. This legislation uniquely integrates plant breeders' rights with farmers' rights and serves as the cornerstone of India's PVP regime. The impact and implementation of this Act are discussed in detail in the subsequent sections.

Plant variety protection in India: To fulfil the requirements of TRIPs agreement India has enacted its own *sui generis* system with the name of Protection of

Table 3 Crop wise plant variety protection (PVP) applications filed at UPOV

S No	Crop name	Crop species	PVP application filed
1	Barley	3	83,532
2	Black Gram	1	12
3	Chickpea	1	864
4	Cotton	2	8,236
5	Cowpea	2	198
6	Groundnut	1	898
7	Lentil	1	447
8	Linseed	2	6074
9	Maize	3	1,74,687
10	Mung bean	1	67
11	Mustard	3	88,538
12	Oats	3	16,234
13	Pea	1	17,500
14	Pigeon Pea	1	21
15	Rice	1	11,967
16	Safflower	1	360
17	Sesame	1	286
18	Sorghum	4	19,496
19	Soybean	1	25,889
20	Sugar Cane	2	818
21	Sunflower	2	81,942
22	Wheat	6	1,43,032
Grand total			6,81,098

Plant Varieties and Farmers' Rights Act (PPV&FRA), 2001 for protecting plant varieties and the rights of both plant breeders and farmers. It recognizes farmers' contributions to conserving, improving, and making available plant genetic resources.

Plant Genetic Resources (PGRs), including landraces, modern and obsolete cultivars, breeding lines, wild relatives, and crop wild species, serve as essential germplasm for crop improvement, enabling the development of high-quality, high-yielding varieties to enhance national food security (Akhund *et al.* 2018). To systematically document these PGRs, the ICAR initiated a germplasm registration process in 1996, with the National Bureau of Plant Genetic Resources (NBPGR), New Delhi, as the nodal agency. Over the past three decades (1996–2024), 2,198 accessions of 261 crop species have been registered, with a notable increase (50–80%) in trait-specific registrations between 2017 and 2021. Cereals and pseudo-cereals dominate registered accessions (35.75%), followed by millets (7.14%), fibre and forage crops (5.91%), grain legumes (10.05%), vegetables (6.18%), and others. The majority of registered accessions belong to ICAR institutes (62.83%), followed by State Agricultural Universities (21.93%), NBPGR (5.96%), CSIR (2.96%), traditional universities (0.73%), private companies (0.55%), farmers (0.18%), and others (4.87%) (Singh *et al.* 2024).

Following the implementation of the PPV&FR Act in 2001 in India, the first plant variety was registered in the year 2007 for black gram with a denomination of *Vishwas*. Subsequently, the registration process of varieties became more systematic, with increasing submission from both public and private institutions. Fig. 3 illustrates the year-wise trends in plant variety submissions. During the initial four years (2007–2010), 2,207 varieties were submitted across different crop categories. The PPV& FR Authority received its highest share of registrations (43.78%) between 2011 and 2015, maintaining a similar pace until 2017. However, submissions declined in the following years due to exhausted pending applications and the COVID-19 pandemic. Recent efforts by the PPV& FR Authority, including awareness campaigns and stakeholder collaboration, have revitalized submission rates over the past three years.

The submitted plant varieties were classified into five groups, Essentially Derived Varieties (0.30%); Extant (Notified) Varieties (10.77%); Extant (VCK) Varieties (10.76%), Farmer Varieties (60.97%), and New Varieties (17.20%). From a total of 160 crops, 20 major crop varieties were selected in the present study, for analysis, based on their legal status at PPV& FRA. These crops spanned cereals (6), cash Crops (1), fruits (1), oilseed (1), pulses (5), spices (1), and vegetables (5). Analysis of registration status revealed that 85.49% of applications were registered, with certificates issued, 74.21% of applications were closed and 70.89% remained under processing. Collectively, these selected varieties accounted for 78.38% of all applications submitted to the PPV&FR Authority.

The crop-wise and applicant-wise registration status of top 20 crop's varieties registered at PPV&FRA is presented in Supplementary Table 1. Rice dominated submissions, accounting for 36.11% of total varieties and 45.20% of certificates issued, followed by maize (7.52% submissions, 7.02% certificates), tetraploid cotton (5.90% submissions, 8.07% certificates), pearl millet (2.61% submissions, 2.68% certificates), wheat (2.56% submissions, 2.72% certificates). Cereals collectively represented 51.79% of all submissions.

Applicant-wise distribution of plant variety registrations: Among applicants, 78.36% of filings were distributed as farmers (46.66%), private organizations (22.24%), public-

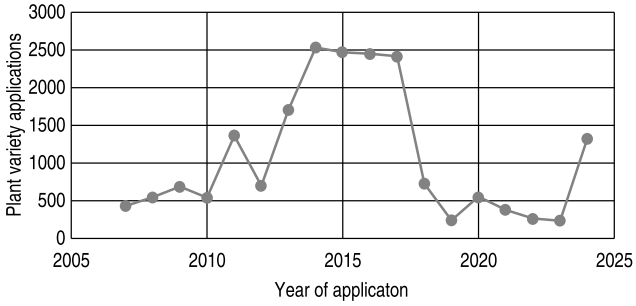

Fig. 3 Year wise plant variety applications submission at PPV&FRA.

funded institutions (9.45%). Geographically, submissions spanned 34 states/UTs, with 55.32% concentrated in Telangana (14.56%), Jharkhand (12.71%), Chhattisgarh (10.14%), Delhi (9.06%), Maharashtra (8.86%). Farmers and farmer organizations accounted for the majority of submissions, comprising 6,259 applications (61.02% of total filings). Notably, the top five farmer applicants who contributed 5.57% of total submissions comprised Dr. Richariya Kisani Samwardhan Samiti (299), All Manipur Trained Medicinal and Aromatic Plants Promoters Consortium (262), Jai Durga Krishak Club (259), Dharohar Samiti (200) and Green Farmers Group (96).

Private organizations submitted 25.69% of total applications (179 entities), with the top five applicants responsible for 10.08% of filings belonging to Nuziveedu Seeds Ltd (822), Syngenta India Limited (437), Kaveri Seed Company Ltd (326), Pioneer Overseas Corporation (231), and Bayer Crop Science Ltd (204).

Investment in crop improvement: The development of new, improved, and trait-specific varieties necessitates coordinated efforts across research, education, and extension systems. Private sector entities actively reinvest up to 30% of their annual turnover into R&D and related activities underscoring their critical role in advancing crop innovation (Vangheluwe *et al.* 2023).

A total of 57 public institutions accounted for 13.26% of all plant variety applications, with the top five contributors submitting 10.28% of total filings. These include ICAR (1,651), Mahatma Phule Krishi Vidyapeeth (128), Professor Jayashankar Telangana Agricultural University (96), University of Agricultural Sciences (93), and Punjab Agricultural University (91). Only six varieties were submitted by individual breeders.

The PPV& FR Authority permits foreign registrations, with 2.12% of total applications coming from 17 countries across Africa (2 countries), Asia (1), Europe (12), North and South America (1 each). The key submitting nations are USA (47.88%), Netherlands (14.78%), Belgium (11.03%), France (7.27%) and Switzerland (7.04%). Half of all foreign applications were received in the last five years (2021–25).

Rice is the leading crop with 36.85% share followed by potato (17.84%), grapes (10.56%), pearl millet (8.45%), maize (7.51%) and others. The type of these varieties indicates that 71.12% were submitted as New, 23.47% as Extant (VKC), and 5.39% and Extant (Notified). The legal status of these applications shows that 38.49% applications were already registered and certificate issued, and 61.50% are in process of grant/registration.

The above discussed trends and status of the plant variety registration at PPV& FRA are self-sufficient to express the need of this act as a sui generis system to protect farmer and breeder's rights. The results of the foreign applications are evident enough to realize the importance and acceptability of the act at international platforms. This system fulfils the requirements of TRIPS agreement as well as protection of the local land races and biodiversity of the country. Farmer (61.02%) and Private (25.69%) variety registration is the source of motivation for the seed industry as well as involvement of different stakeholders in the food production system. The IP protection of the new plant varieties and farmers' rights in the context of global agricultural practices and Sustainable Development Goals (SDGs) reveals that India's sui generis system represents a more balanced approach by addressing the needs of the farming community, and environmental protection along with breeders (Wu 2024).

In an investigation of registration of plant varieties under the PVP&FRA, Rani and her team found that Act has helped in strengthening the agriculture ecosystem by protecting the crop diversity, farmer's access to quality seed, mechanism for protecting variety developed by farmers, involvement of entrepreneurs (breeders) and industry at large (Rani *et al.* 2020).

To ensure the availability of these innovations to its end users i.e. farmers, seed producers, public and private organizations, Ministry of Agriculture and Farmers Welfare, Government of India institutionalized a system for availability/distribution of release/notified varieties and maintained its records on Seednet India Portal. The overall scenario of this portal's database is analysed and presented in the following paragraphs.

Seednet India portal: The SeedNet Portal (https://seednet.gov.in/) is a national initiative providing comprehensive data on seed quality, including released/notified plant varieties, seed availability, demand, and testing facilities. As per the portal, 14,574 plant varieties have been released/notified for cultivation across India, spanning 188 crops from 22 crop groups (Supplementary Table 2). Cereals dominate with 21.96% of total varieties, followed by millets (15.41%), oilseeds (12.05%), pulses (11.83%), and fruits and vegetables (10.98%). The forage group includes the highest number of crops (32), followed by oilseeds and cucurbits (19 each), and pulses and fruit crops (16 each).

Among the 188 crop species, the top ten crops account for 49.26% of all varieties: paddy/rice (16.12%), maize (6.59%), wheat (4.85%), cotton (4.51%), brinjal (3.27%), tomato (3.10%), sorghum (3.09%), pearl millet (2.82%), Bengal gram (2.47%), and chilli (2.45%). The remaining 178 crops constitute 50.74% of varieties (Supplementary Table 2).

Year-wise analysis revealed that 64.16% of these varieties were notified in the last 25 years (2000–2024), indicating a significant increase in recent decades (Supplementary Fig. 1). These varieties were developed and released by 31 state and union territories, along with central government agencies. The Central Government alone accounted for 47.94% of notifications, while Chhattisgarh was the leading state (22.45%), followed by Uttar Pradesh (3.57%), Tamil Nadu (2.43%), Jammu & Kashmir (2.38%), Maharashtra (2.36%), and others.

The combined effort of research institutes, PPV&FRA and other line departments ensure the availability of quality seeds for further multiplication and distribution to farmers.

An analysis of seed availability data from Seednet portal from 2016–17 to 2024–25 indicates a consistent 10.21% surplus in quality seed supply compared to demand (Dadlani *et al.* 2025).

Patenting trends in seed and planting material innovations: Protection of seed and planting material innovations extends beyond plant variety registration under UPOV and PPV&FRA, with other intellectual property (IP) tools such as patents also being utilized by various Plant Breeding Organizations (PFOs). To analyse crop-wise patenting trends, 25 selected crops were used as keywords for database searches, with only patents mentioning these crops in their claims included for analysis. Results are shown in Supplementary Table 3.

The findings revealed that 36.86% of patents pertain to cereal crops, followed by cash crops (36.68%), oilseeds (23.90%), and pulses (2.54%). Notably, 77.38% of the total applications (2,089,209) were concentrated in just five crops: cotton (35.68%), rice (18.24%), soybean (10.70%), wheat (9.39%), and sesame (3.35%), while the remaining 20 crops accounted for only 22.61%. Pulses were the least represented in patent filings. These patents primarily span food chemistry, biotechnology, basic materials chemistry, organic fine chemistry, pharmaceuticals, and related fields.

The top five patent-filing offices (PFOs) for these innovations are China (CN), the United States (US), the European Union (EU), India (IN), Japan (JP), and Korea (KR). The Indian Patent Office (IPO) emerges as the preferred PFO for pearl millet, black gram, and groundnut, and the second choice for sugarcane. For cowpea, pigeon pea, maize, chickpea, and millet, India ranks as the fourth choice. Notably, India features among the top five PFOs for all but 12 crops (where it ranked 6th or 7th). Key institutional filers include Pioneer Hi-Bred International, Monsanto Technology, BASF, Bayer, China Agricultural University, L'Oréal, and Nestlé. Indian entities such as the Council of Scientific & Industrial Research (CSIR) and the Defence Research & Development Organisation (DRDO) have also secured patents in these domains.

The temporal trends and legal status show that 15.15% patents were filed before 2006 thus already lapsed due to completing their 20 years' time span, followed by 7.78% in 2006–2010, 19.31% in 2011–2015, 35.59% in 2016–2020, and 22.14% after 2020. The legal status of these applications ensures that 30.96% patent applications were granted to their applicants, and 9.10% applications are in process of grant.

These patent filing trends correlate with national and international seed import-export dynamics, further reinforcing India's advancements in crop-based research and the commercial seed sector. To evaluate the role of academic institutions in agricultural innovation, an assessment of patents from the top 100-agricultural universities was conducted, the findings of which are discussed in the following subsections.

Patent filing trends at top 100-agricultural universities: According to Research.com, the top 100 agricultural universities are distributed across 25 countries worldwide. The United States leads with 31 institutions, followed by Australia (10), while Canada, the United Kingdom, and Germany each have six. The remaining 41 universities are spread across 20 other countries. India is represented by two institutions: Banaras Hindu University (ranked 390) and Aligarh Muslim University (ranked 24).

A detailed country-wise breakdown of these patent applications is provided in Supplementary Table 4. As per the Questel Orbit patent search engine, the patent filing trends of these agricultural universities shows that 97.21% patent applications were filed by 56 universities of the world that belong to only five countries of the world, viz. China (72.81%), USA (11.61%), Japan (9.24%), Australia (1.78%), and Canada (1.76%). The legal status of these patent applications reveals that 52.22% applications are already granted and also in process of the grant; but 47.78% applications are now in public domain due to lapse of their 20 years' time span and many more got abandoned due to lack of fulfilling the grant criterions as per respective PFOs.

The patent filing trends of these universities are also supporting to the crop-based research institutes and plant variety registration domains.

Patent filing trends at crop science based research institutes of ICAR: To know about these trends in the Indian scenario, ICAR's patent portfolios were assessed as follows:

Crop science research institutes under the Council of the Indian Council of Agricultural Research (ICAR) began filing patents for their innovations starting in 1950. The first patent application was submitted by the ICAR-Indian Agricultural Research Institute (IARI), New Delhi, in that year. Between 1950 and 2000, three ICAR institutes collectively filed 43 patent applications. This number tripled to 138 applications in the following decade (2001–2010), driven by the implementation of ICAR's Intellectual Property Rights (IPR) and technology commercialization guidelines in 2006. These guidelines aligned with the World Trade Organization's (WTO) Trade-Related Aspects of Intellectual Property Rights (TRIPS) agreement, which India ratified in 1997.

Further institutional support, including the NAIF, contributed to a 39.44% growth in patent filings between 2011 and 2020, a trend that has continued into the most recent four years (2021–2024). A total of 25 crop science research institutes participated in this innovation drive, with ICAR-IARI, New Delhi, leading with 173 patent applications. Other notable contributors include ICAR-National Institute for Plant Biotechnology (44 applications), ICAR-National Bureau of Agricultural Insect Resources (28), ICAR-Central Institute for Cotton Research (19), ICAR-Sugarcane Breeding Institute (17), and ICAR-National Research Institute for Integrated Pest Management (17).

An analysis of the legal status of these patents reveals that 25% have entered the public domain due to expiration or abandonment, while 29% are under review. The Indian Patent Office (IPO) has granted 46% of the applications. To facilitate commercialization, 12 ICAR institutes have entered into 140 licensing agreements with 117 public and

private sector organizations, ensuring these innovations reach end-users effectively.

Plant variety commercialization/licensing at ICAR: Technology commercialization stands as a pivotal objective of India's National IPR Policy 2016, aiming to bridge the gap between agricultural innovations and their industrial application. As the premier agricultural Research and Education (R&E) organization in India, ICAR oversees 113 specialized institutes, with 32 institutions specifically focused on seed and planting material development for crops, horticulture, and natural resource management. The Indian agricultural research system has significantly contributed to national food security through the development and dissemination of improved crop varieties. The adoption of non-exclusive licensing models (Bhooshan *et al.* 2024) has proven particularly effective in this sector by enabling multiple stakeholders to participate in seed production. This approach, combined with institutional mechanisms like the Food Corporation of India (FCI) and the Commission for Agricultural Costs and Prices (CACP), along with advancements in irrigation, fertilizer use, and farm mechanization, has been instrumental in transforming India's agricultural productivity (Chand and Khadka 2022). Effective valuation in crop variety licensing remains crucial for maintaining research sustainability and ensuring balanced economic returns across the technology transfer value chain (Stanishkar *et al.* 2024). The following sections present a detailed analysis of ICAR's technology commercialization and licensing initiatives, examining their outcomes and broader impacts:

Year wise trends: The commercialization of plant varieties under ICAR's institutional framework began in 2007 with the rice hybrid "Ajay (CRHR 7)" developed by ICAR-National Rice Research Institute (NRRI), Cuttack (PPVFRA Registration No. REG/2011/499). Following the implementation of ICAR's three-tier IP management system, technology transfer activities gained momentum, resulting in 62 licensing agreements (2.69% of total) between 2007 and 2010.

The establishment of the NAIF in 2014 marked a significant acceleration in commercialization efforts. This institutional support, coupled with enhanced awareness programs and business incubation initiatives, facilitated the execution of 311 licensing agreements (13.52% of total) from 2011–2015, 523 agreements (22.74%) between 2016 and 2020 and 1,403 agreements (61.02%) from 2021–2024. This exponential growth, particularly the four-fold increase in licensing activity during 2021–2024 compared to the previous five-year period, demonstrates the effectiveness of ICAR's IP policy framework and capacity-building initiatives in seed and planting material research. The year-wise progression of ICAR's technology commercialization efforts is presented in Supplementary Fig. 2.

Technology wise licensing trends: The distribution of licensing agreements across crop categories is presented in Supplementary Fig. 3, encompassing 12 major crop groups. Vegetable crops represented the most diverse group with 25 crop species and 148 varieties, followed by fruits (17 species/56 varieties), spices (including seed spices; 13/27), cereals (6/143), and pulses (5/24). Cereal crop varieties were in highest demand with 1,506 (65.50%) licensing agreements, followed by vegetables (18.61%), Fruit (4.69%), Spices (3.69%) and Oilseeds (2.56%) and others. This cereal-centric trend mirrors findings from Ethiopian agricultural systems, where cereal commercialization has proven effective in boosting farmer incomes (Ayele 2023). Notably, 27 licenses demonstrated particular market engagement by executing more than 10 agreements each, collectively representing 15.22% of total licensing activity. The licensing analysis reveals significant concentration among protected varieties, with 25 varieties from just nine crop species accounting for 40.71% of total PPV&FRA-protected licenses. Five wheat varieties, HD-3086, DBW-173, HD-3386, HD-3385, and HD-3226, have dominated the licensing landscape, collectively representing 30.23% of all agreements. Other crops with multiple licensed varieties included Mustard (5 varieties), Onion (4 varieties), Pigeon pea (3 varieties), Guava (3 varieties). This concentration pattern highlights the commercial viability and market preference for these high-performing varieties among licensees.

Institute wise trends: ICAR institutes have played a pivotal role in driving agricultural innovation and technology transfer, facilitating the dissemination of improved varieties to both public and private sector organizations. A total of 32 ICAR institutes contributed 458 varieties of 83 crops, licensed through 2,299 agreements with 975 organizations and individual entrepreneurs. ICAR-IARI, New Delhi is the leading institute with 139 plant varieties licensed to 453 public and private organization via 1,122 licensing agreements. Other key institutes include ICAR-Indian Institute of Vegetable Research (IIVR), Varanasi (44 varieties/30 licenses/73 agreements); ICAR-Indian Institute of Horticulture Research (IIHR), Bengaluru (42/59/115); ICAR-National Rice Research Institute (NRRI), Cuttack (38/46/111); ICAR-Central Plantation Crop Research Institute (CPCRI) (19/14 /26); and others.

State wise trends: ICAR's efforts in technology licensing resulted in transfer innovations from 32 institutes to 24 states and union territories of the country. These states were classified as per their administrative zones, where Northern Zone is leading with its 45.71% share in total licensing, followed by Southern Zone (19.18%), Western Zone (17.52%), Central Zone (11.91%), Eastern Zone (5.17%), and North-Eastern Zone (0.47%). Punjab is the leading state 454 licensing agreements with 175 licensees for 39 varieties of 12 crops, followed by Haryana (405/148/43/11), Maharashtra (302/148/118/36), Telangana (223/66/122/27), New Delhi (114/45/70/24), and others (Supplementary Table 5).

IP protected technology licensing: Plant variety registration with the PPV&FR Authority serves as a pivotal institutional mechanism, simultaneously enhancing commercial viability and academic visibility of ICAR's

crop-based research institutes. To date, 240 protected varieties across 54 crops have been registered, accounting for 80.77% of total licensing activity in seed and planting material demonstrating the direct correlation between formal IP protection and successful technology commercialization. This success is driven by multiple synergistic factors, *viz.* Sustained research across ICAR's crop science institutes; Implementation of structured IP management and technology transfer guidelines; Strategic alignment with India's National IPR Policy (2016) which emphasizes commercialization; Establishment of the agri-business ecosystem through NAIF.

Prior to 2007, institutional mechanism for technology commercialization/licensing in agricultural research were absent., Over the last 18 years, Council's three tier IP management system enhanced the protection and transfer of its intellectual assets. The system has enabled collaborations with over 2,779 public and private sector organizations and individual entrepreneurs, facilitating the transfer of 1,881 agricultural innovations through more than 5,000 licensing agreements. These innovations have reached all 33 states and union territories across India. Seed and planting material alone account for 43.25% of the total licensing share (Datt *et al.* 2018, Singh *et al.* 2022).

ICAR's seed and planting material innovations have achieved pan-India reach, driving significant growth in the productivity and production of cereals, oilseeds, pulses, fruits, and vegetables. This progress underscores the Council's pivotal role in meeting the nation's growing demand for high-quality food. Notably, this initiative stands as the most comprehensive technology transfer effort among global agricultural research organizations, with no comparable examples documented in international literature.

Agri-business/start-up initiatives: ICAR has established Agri-Business Incubation (ABI) Centres to promote entrepreneurship across 50 of its research institutes. Among these, seven centres specialize in areas such as crop improvement, millets, oilseeds, rice, and natural resource management. According to the Startup India database, 6,472 start-ups are currently active in agriculture and allied sectors, with Agri-Tech Start-ups are leading the domain, accounting for 2,791 ventures. To strengthen the agri-business environment within ICAR these ABI Centres operational from 2016–17 onwards, providing support to entrepreneurs, innovators, scholar, start-ups at various ICAR institutes. Between 2016–2024, these initiatives have successfully motivated 1,356 entrepreneurs and startups to launch their own agri-business ventures (ICAR 2024).

The critical role of seed systems in ensuring global food security has long been recognized by research institutions worldwide, prompting the establishment of comprehensive legal frameworks through specialized acts, policies, and international treaties. These institutional mechanisms have fostered continuous innovation in seed and planting material research, strengthened intellectual property (IP) protection and expanded global market access for improved varieties. This meta-analysis of global IP trends identifies the United States, China, the European Union, the Russian Federation, India, and Brazil as key players. These countries demonstrate consistent growth in variety protection filings, dynamic trade in planting materials, and significant contributions toward achieving SDG targets related to food security. These nations are at the forefront of efforts to meet the nutritional needs of growing populations.

The analysis revealed that the global seed industry is predominantly concentrated in European Union, USA, and South-East Asia. Cereal and vegetable crops lead both in research and IP protection efforts in India as well as internationally. Supplementary Fig. 4 illustrates the global landscape of seed business.

To fully harness the potential of seed systems in combating hunger, we underscore the need for targeted research tailored to region-specific climatic conditions, dietary patterns, and nutritional requirements. This must be supported by robust policy frameworks that enhance IP protection, facilitate technology transfer, and streamline commercialization pathways. Additionally, institutional capacity building in variety development, seed production, and distribution networks is essential to ensure the widespread availability of climate-resilient and nutrition-sensitive planting materials. By adopting this multi-dimensional approach, national and international research organizations can develop sustainable seed systems capable of responding to the diverse and evolving demands of global food and nutritional security.

This study highlighted the transformative impact of institutionalizing seed research and IP protection while emphasizing the need for collaborative, policy-driven strategies to effectively scale innovations. Future efforts must prioritize localized solutions, strengthen global partnerships, and accelerate the commercialization of high-quality planting materials to achieve meaningful progress toward a hunger-free world.

Seed is the soul of agriculture research, policy, and development. To get the full expression of this soul, stakeholders of the seed sector must enhance protection through existing IPR frameworks, and facilitate its commercialization through production agencies. These initiatives will motivate young entrepreneurs and startups to contribute to the Zero Hunger target of the SDGs.

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