Weed Science

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Review

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A global perspective of education in weed science

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Abstract

In modern agriculture, weed problems are predicted to worsen and become more complicated as a result of increasing invasiveness, herbicide resistance, and emphasis on high-input methods. Weeds cause huge economic yield losses that range from US$100 million to US$26 billion globally. The knowledge of weed science has offered success in the past through effective, reasonably priced, and secure technologies; specifically, synthetic herbicides to effectively control weeds in agroecosystems. Weed science is accepted and adopted by many universities with teaching, research, and/or extension programs in agriculture. Globally, approximately 7% of all the universities offering agricultural education have dedicated weed science departments focusing on weed biology, ecology, and management. Some universities also offer weed science degree programs or at least certain courses in their degrees related to associated disciplines, such as plant protection, agronomy, and ecology. Although substantial advances have been made in weed science, such as a separate weed science discipline, specialized journals, and specific weed science societies and conferences worldwide, many constraints (e.g., lack of trained weed scientists) and barriers to adoption of new weed science technologies remain. Slow modernization in weed science research and low funding has slowed the progress of this discipline. New curricula in the weed science discipline should focus on the role of biochemistry, evolutionary biology, molecular biology, and genetics in weed science research.

Introduction

Weeds are plants that are adapted to growing in agricultural lands while not being specially cultivated (Tretyakova et al. 2020). According to the Weed Science Society of America, a weed is "a plant that causes economic losses or ecological damage, creates health problems for humans or animals, or is undesirable where it is growing" (WSSA 2023a). Weeds, due to their higher adaptability and resilience, pose a persistent threat to agricultural production.

Weed science knowledge can be divided into three main categories: applied, fundamental, and socioeconomic (Jordan et al. 2016). Applied knowledge includes agronomy and weed science, which deals with the development and improvement of control or management methods using cultural, mechanical, chemical, and biological control, and integrated weed management (IWM) techniques. Fundamental aspects of weed science include key aspects of plant biology and ecology, such as genetics, dispersal mechanisms, and population and seedbank dynamics. The research into these fundamental aspects provides a better understanding of weeds' life cycles to develop/optimize effective management programs. Socioeconomic knowledge includes topics within sociology and economics that deal with weeds' impacts and consequences of effective or ineffective management regimes in society (Jordan et al. 2016).

Weed science is a relatively new discipline in plant science that has evolved significantly over the past few decades. The technological revolution in agriculture that is exemplified by the widespread development and quick adoption of synthetic herbicides has greatly contributed to the establishment of weed science as a separate discipline. This discipline focuses on different approaches to weed control through the diversity of weed research, developments in weed science technologies, and obstacles to future technological advancements.

The effects of chemical weed control on on-farm management techniques, their impact on the goals, and programs for agricultural education and research are also covered under the weed science discipline. Weed science has offered success in the past by contributing to effective, reasonably priced, and secure technologies to manage weeds in a number of agronomic and environmental settings (crop types, weed densities, and weed types).

There are many universities worldwide that were specifically established to pursue education and research in agriculture and applied sciences, a prime example being the United States (U.S.) land-grant universities. Similarly, several big universities conducting teaching and research in multiple disciplines have dedicated organizational units (faculties, colleges, schools, institutes, centers, etc.) delivering education, research, and outreach in agricultural sciences. From a weed science point of view, several universities have focused on weed science departments, while others subsume weed science within the crop protection or agronomy departments. Also, different research institutes offer several services, from working on projects under ecology, biology, and management to providing extension services for controlling weeds and decreasing economic losses. This article presents precise knowledge about the aggregate number of universities, agricultural universities, and universities involved in weed science education worldwide. Moreover, a brief history of weed science and its scope, weaknesses, and prospects are also discussed in this review. In addition, updated information about books, conferences, and journals related to the weed science discipline is provided.

The synthesis of this information will provide an updated account of the progress and scope of weed science and the challenges it faces as a unique but very important subdiscipline of agriculture. This will help educators, researchers, practitioners, and prospective students to determine the value and potential of weed science in crop protection. We also believe the information presented in this review will encourage the next generation to engage in this rapidly evolving yet rewarding discipline of agricultural sciences.

History of Weed Science

Historical books and articles about weed science show that weeds have been known to exist for thousands of years, since the start of settled food production. During that time, humans also discovered that the output of their preferred crop, typically coarse-grain cereals, was highest when it was cultivated in the absence of competitive plants that grew in the same habitat. Such species would have been manually eliminated by our forebears to mitigate the yield reductions caused by weed competition. This was an early attempt to suppress weed growth in inhabited areas transitioning to an agricultural-based lifestyle.

Archeological artifacts and ancient writings also certify the decline in yield due to weeds and the use of several tactics for managing them (Radosevich et al. 1997). By following the historical trajectory of weed science in Canada and the United States, Timmons (2005) determined that before 1200 CE or even 1500 CE, only a small number of agricultural leaders and farming communities identified weeds as a major problem and developed an interest in weed management. However, the development of weed science as a separate field of study does not correspond with the presence of weeds in cropped and non-cropped areas. The history of weed research is likely less than 100 years old, paralleling the history of industrialized agriculture (Radosevich et al. 1997). Some plant protectionists and weed scientists would argue that the invention of phytotoxic chemicals and herbicides for weed control marked the beginning of the scientific study of weeds. Early in the 20th century, sulfuric acid and inorganic copper salts were the first substances utilized to suppress weeds (Timmons 2005). The production of 2,4-D herbicide by Pokorny (1941) and the discovery of its herbicidal properties as a plant growth regulator by Hamner and Tukey in 1944 were the first accounts of a synthetic organic chemical used to manage weeds (Stephenson et al. 2001). These events started planned weed management opportunities and, some would argue, the inception of weed science as a specific discipline.

Weed science as a discipline has succeeded in connecting university researchers, industrial researchers, university extension workers, and farmers to effectively introduce chemical weed control and other weed management practices. This integration can be considered as a model for pushing new technology into mainstream society. Wilfred W. Robbins was the professor who developed the first weed science course and co-wrote the first textbook on weed management, *Weed Control*, in 1942 (Zimdahl 2010). This book served as a source of the widespread introduction of weed science as a specific course and later as a separate discipline in the United States and worldwide (Zimdahl 2010). Alden Springer Crafts from the United States was the first person to claim the title of “weed scientist.” Robbins provided the necessary momentum to create the scientific study of weeds, but Crafts provided credibility to weed science through research work and prolific writing (Zimdahl 2010). George Knowles was the first person who worked full-time as a weed scientist in Canada (Timmons 2005).

Today, weed science is a well-established discipline, but it is still relatively smaller compared with allied crop protection disciplines such as entomology and plant pathology. In its relatively short history, this dynamic discipline has seen dramatic booms and busts from widespread adoption and prolific success of chemical herbicides to the rapid evolution of large-scale herbicide-resistance evolution across the globe challenging conventional, simplistic weed control programs. We are at the crossroads of ever-increasing herbicide-resistance issues, changing land use and management systems, and impressive technological advancements and digital disruption. On the other hand, significant progress has been made, and there is a further push to explore weed management implications of agroecology and integrated pest management (IPM) principles (Riemens et al. 2022). These factors are shaping weed science as a highly interactive, holistic, and technologically advanced field of agricultural sciences.

Weed Science Education Worldwide

Globally, several educational institutes work in numerous disciplines. Higher (university-level) education particularly focuses on specialized, discipline-wise educational training and research. The United States alone has the highest number of universities accounting for 3,982 in the public and private education sectors (Table 1). Russia has 3,000 universities, 47 in the agriculture category. Underdeveloped countries in Asia and Africa still have less focus on agricultural studies. Overall, many universities were specifically established to pursue research and education in the field of agriculture, while many others have agriculture faculties offering different courses and degree programs related to agriculture.

From the weed science point of view, several universities have special weed science departments (Table 1), while other universities provide education on weed science aspects within crop protection, agronomy, and ecology departments. Also, different research institutes offer several services from working on projects under ecology, biology, and management to providing extension services for controlling weeds and decreasing their economic losses. Moreover, a lot of work has been compiled by several authors in the form of specific books that focus on weed

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Table 1. Total number of universities, agricultural universities, and universities involved in weed science education worldwide.[a]

Country	Number of universities	Universities with agriculture faculties	Universities with weed science departments	Source
Afghanistan	179	15	0	Ministry of Higher Education, Afghanistan 2019
Algeria	64	3	0	Algeria Ministry of Higher Education and Scientific Research 2023
Angola	18	1	0	Ministry of Higher Education, Science, Technology and Innovation of Angola 2023
Argentina	85	11	2	Federation Universitaria Federation 2023
Australia	189	13	0	Australian Government Tertiary Education Quality and Standards Agency 2023
Austria	35	4	0	Federal Ministry of Education, Science and Research, Austria 2023
Azerbaijan	52	9	0	Suleymanov 2020
Bangladesh	161	23	0	University Grants Commission of Bangladesh 2023
Belarus	50	2	0	Belarusian System of Higher Education 2023
Belgium	25	3	1	University Directory Worldwide 2023a
Benin	17	1	0	All University Info 2023a
Bolivia	67	3	0	Ministry of Education of Bolivia 2023
Brazil	127	25	5	Ministério da Educação 2023
Bulgaria	45	7	0	European Education Directory 2023
Burkina Faso	17	1	0	UniRank 2023
Burundi	21	2	0	UniRank 2023
Cambodia	105	12	2	Ministry of Education, Youth and Sport, Cambodia 2023
Cameroon	159	9	1	Ministry of Higher Education Cameroon 2023
Canada	98	12	1	Canadian Visa Organization 2023
Chad	9	1	0	UniRank 2023
Chile	61	9	1	MINEDUC, 2023
China	3,012	289	6	Ministry of Education, The People's Republic of China 2023
Colombia	115	9	1	Colombia Education Info 2023
Côte d'Ivoire	10	2	0	All University Info 2023b
Czech Republic	64	9	0	Ministry of Education, Youth and Sports, Czech Republic 2020
Democratic Republic of the Congo	43	3	0	University Directory Worldwide 2023j
Denmark	17	7	0	Ministry of Education and Research, Denmark 2023
Ecuador	70	2	0	Ministry of Education, Ecuador 2023
Egypt	63	9	1	Enterprise 2021
Ethiopia	60	2	0	Ministry of Education, Ethiopia 2023
Finland	46	3	0	Ministry of Education and Culture, Finland 2023
France	270	50	0	Ministry of Education, France 2023
Germany	400	43	3	University Directory Worldwide 2023b
Ghana	92	5	1	All University Info 2023c
Greece	20	4	0	Ministry of Education and Religious Affairs, Greece 2023
Guinea	3	0	0	All University Info 2023d
Hungary	65	3	0	Ministry of Natural Resources, Hungary 2023
India	1027	71	4	University Grants Commission, India 2023
Indonesia	125	4	0	Welch and Aziz 2022
Iran	428	23	2	Ministry of Science, Research and Technology, Iran 2023
Iraq	80	15	1	MOHESR 2023
Israel	66	7	0	Ministry of Aliyah and Integration, Israel 2023
Italy	116	21	2	University Directory Worldwide 2023c
Japan	795	56	4	Japan Education Info 2023
Jordan	29	6	1	MOHE 2023
Kazakhstan	149	15	2	All University Info 2023d
Kenya	73	7	1	Commission for University Education2023
Kyrgyzstan	56	11	1	European Commission 2023a
Laos	67	3	0	Open Development Mekong 2023
Lebanon	32	5	1	All University Info 2023f
Liberia	38	31	2	Boateng 2020
Libya	83	5	0	Ministry of Higher Education and Scientific Research 2023
Madagascar	12	1	0	Ministry of Education, Madagascar 2023
Malawi	13	2	0	Ministry of Education, Republic of Malawi 2023
Malaysia	67	13	1	Unipage 2023
Mali	10	2	0	UniRank 2023
Mexico	3,587	27	3	Statista 2023a
Morocco	24	2	0	Morocco Academia 2023
Mozambique	7	2	0	University Directory Worldwide 2023d
Myanmar	163	8	1	Myanmar Education Info 2023
Nepal	11	2	0	University Grants Commission, Nepal 2023
Netherlands	73	8	0	University Directory Worldwide 2023h
New Zealand	84	8	1	Ministry of Education, New Zealand 2023
Niger	3	1	0	University Directory Worldwide 2023e
Nigeria	170	11	1	Nigeria Federal Ministry of Education 2023

(*Continued*)

Table 1. (*Continued*)

Country	Number of universities	Universities with agriculture faculties	Universities with weed science departments	Source
North Korea	190	30	4	Ministry of Education, North Korea 2023
Norway	48	3	0	NOKUT 2023
Oman	36	7	0	Ministry of Higher Education, Research Innovation, Oman 2023
Pakistan	233	36	1	Higher Education Commission Pakistan (2023)
Papua New Guinea	8	1	0	National Strategic Plan Taskforce, Independent State of Papua New Guinea 2023
Peru	143	17	2	Ministerio de Educación 2023
Philippines	1,975	11	2	OPRKM-KMD 2023
Poland	457	23	3	Ministry of Science and Higher Education, Poland 2023
Portugal	46	2	0	Edubilla 2023
Romania	92	3	0	Ministerul Educației 2023
Russia	683	47	0	University Directory Worldwide 2023i
Rwanda	31	2	0	Ministry of Education, Rwanda 2023
Saudi Arabia	67	5	0	Ministry of Education, Saudi Arabia 2023
Senegal	17	4	0	All University Info 2023e
Serbia	18	2	0	Educational Research Association of Serbia 2023
Sierra Leone	4	1	0	Ministry of Technical and Higher Education, Republic of Sierra Leone 2023
Singapore	34	3	0	EY-Parthenon 2023
Slovakia	33	6	0	Ministry of Education, Science, Research and Sport of the Slovak Republic 2023
Somalia	24	3	0	University Directory Worldwide 2023f
South Africa	26	2	1	Higher Education and Training, Republic of South Africa 2023
South Korea	179	7	0	Statista 2023b
South Sudan	12	1	0	UniRank 2023
Spain	82	7	0	Spain Education Information 2023
Sri Lanka	39	6	0	University Grants Commission, Sri Lanka 2023
State of Palestine	49	2	0	Palestinian Ministry of Education & Higher Education 2023
Sudan	38	2	0	University Directory Worldwide 2023g
Sweden	39	5	1	Government of Sweden 2023
Switzerland	44	4	0	EAER 2023
Syria	27	4	0	Ministry of Higher Education and Scientific Research, Syria 2023
Tajikistan	30	2	0	European Commission 2023b
Tanzania	47	2	0	Ministry of Education Science and Technology, Tanzania 2023
Thailand	150	11	2	Office of the Higher Education Commission, Bureau of International Cooperation Strategy, Ministry of Education, Thailand 2008
Togo	4	1	0	UniRank 2023
Tunisia	23	2	0	Tunisia Education 2023
Türkiye	209	12	0	Council of Higher Education Turkey 2023
Turkmenistan	23	3	1	Ministry of Education of Turkmenistan 2023
Uganda	59	19	1	Ministry of Education and Sports Uganda 2023
Ukraine	664	19	3	Education fair.nl 2023
United Arab Emirates	299	11	0	Ministry of Education, United Arab Emirates 2023
United Kingdom	164	23	2	Statista 2023c
United States	3,982	96	40	WSSA 2023c
Uzbekistan	56	6	0	Ministry of Higher Education, Science and Innovations of the Republic of Uzbekistan 2023
Venezuela	47	6	0	All University Info 2023f
Vietnam	237	21	1	Statista 2023d
Yemen	30	4	0	Ministry of Higher Education and Scientific Research, Yemen 2023
Zambia	87	2	1	Higher Education Authority Zambia 2023
Zimbabwe	14	0	0	University Directory Worldwide 2023k

[a]The list of universities comes only from the countries that have a population of more than 5 million. Countries are ordered alphabetically.

ecology, biology, and management options (Table 2). Also, there are specialized journals and specific weed science societies (Table 3) that are working for the betterment of the weed science discipline.

Globally, approximately 7% of all universities that offer agricultural education have dedicated weed science departments that work on weed biology, ecology, and management (Table 1). Some universities also offer weed science degree programs or at least certain courses in degrees related to associated disciplines, such as plant protection, agronomy, and ecology. Substantial advances, such as separate weed science disciplines and known specialized journals and conferences in weed science, have been made worldwide. Also, there are international, regional, and national weed science societies that work to promote and encourage the development of weed- related knowledge and the impact of weeds on society. For example, the WSSA states that its basic purpose is that it "promotes research, education, and extension outreach activities related to weeds; provides science-based information to the public and policy makers; fosters awareness of weeds and their impacts on managed and natural

Table 2. List of some important books related to weed science

Title	Author(s)/editor(s)	Year of publication[a]	Publisher
Applied Weed and Herbicide Science	Kassio Ferreira Mendes, Antonio Alberto da Silva (editors)	2022	Springer
Biology and Management of Problematic Crop Weed Species	Bhagirath S. Chauhan (editor)	2021	Academic Press
Biology, Physiology and Molecular Biology of Weeds	Mithila Jugulam (editor)	2021	CRC Press
Fundamentals of Weed Science (5 editions)	Robert L. Zimdahl (author)	Latest edition (2018) First edition (1993)	Academic Press
Weed Control: Sustainability, Hazards and Risks in Cropping Systems Worldwide	Nicholas E. Korres, Nilda R. Burgos, Stephen O. Duke (editors)	2018	CRC Press
Non-chemical Weed Control	Khawar Jabran, Bhagirath Chauhan (editors)	2018	Academic Press
Identification and Control of Common Weeds (Volumes 1–3)	Zhenghao Xu, Le Chang (authors)	2017	Springer
Integrated Weed Management for Sustainable Agriculture	Robert L. Zimdahl (editor)	2017	Burleigh Dodds Science Publishing
Manipulation of Allelopathic Crops for Weed Control	Khawar Jabran (author)	2017	Springer Cham
Recent Advances in Weed Management	Bhagirath S. Chauhan, Gulshan Mahajan (editors)	2014	Springer
Principles of Weed Control	Steven A Fennimore, Carl Bell (editors)	2014	California Weed Science Society
Herbicide Resistance in Weeds and Crops	J. C. Caseley, G. W. Cussans, R. K. Atkin (authors)	2013	Butterworth-Heineman
Weed Biology and Climate Change	Lewis H. Ziska, Jeffrey Dukes (authors)	2011	Wiley-Blackwell
A History of Weed Science in the United States	Robert L. Zimdahl (author)	2010	Elsevier
Ecology of Weeds and Invasive Plants (3 editions)	Steven R. Radosevich, Jodie S. Holt, Claudio M. Ghersa (authors)	Latest edition 2007	Wiley Interscience
Weed Science: Principles and Practices (4 editions)	Thomas J. Monaco, Stephen C. Weller, Floyd M. Ashton (authors)	Latest edition 2002	Wiley-Blackwell
Molecular Biology of Weed Control	Jonathan Gressel (author)	2002	CRC Press
Weed Control, (3 editions)	Wilfred W. Robbins, Alden S. Crafts, and Richard N. Raynor (authors)	Latest edition 1962 First edition 1942	McGraw-Hill

[a]The books are listed in descending order (newest to the oldest).

ecosystems; and promotes cooperation among weed science organizations across the nation and around the world" (WSSA 2023b). Several authors have written comprehensive literature in the form of books (Table 2) and review articles (Buddenhagen et al. 2022; Flessner et al. 2021; MacLaren et al. 2020; Westwood et al. 2018) that specifically cover the discipline of weed science.

Scope of Weed Science

Weed science is a broad field that addresses significant biotic stresses that can cause huge economic losses to the agricultural sector and economy of any country, leading to exacerbating the problem of food insecurity. In a comprehensive analysis, Oerke (2006) reported that weeds potentially cause up to 34% loss to crop yields globally. These losses are much greater than those caused by insect pests and diseases that reduce crop yields by 18% and 16%, respectively (Oerke 2006). Due to their persistent nature, weeds are typically given less attention than they deserve. Farmers pay more attention to unexpected, unanticipated epidemics of insect pests or diseases, because they are less accustomed to their presence (Moss 2019). Weeds, on the other hand, are often considered to be a "business as usual" kind of problem, overlooking the magnitude of damages they pose to crop productivity and quality. A parallel condition exists in the public healthcare sector: policy makers devote the most resources to handling acute diseases compared with chronic diseases, which usually receive little attention (Fernandez-Quintanilla et al. 2008).

One of the greatest strengths of weed science is that it offers an arguable and problem-solving approach (Fernandez-Quintanilla et al. 2008). In this context, this discipline can be considered a model that combines several disciplines and utilizes a systematic approach to resolve practical issues. In addition, the weed science discipline is an exceptional example of how to cover the gap between scientific knowledge and its practical management, offering nonfragmented scientific knowledge and practical advice and opportunities to the end-users.

Weed science has had great success in effectively, affordably, and safely managing the weeds in a wide range of crops. Although a huge portion of this achievement has been due to the availability of low-cost, effective synthetic herbicides, sole reliance on chemical control has led to the widespread herbicide-resistance evolution in addition to increasing environmental health concerns (Gaines et al. 2020). A variety of cultural, biological, physical, and IPM-oriented weed management techniques have also been developed and introduced at a commercial scale, as a result of coevolution with the societal request for more environment-friendly crop management systems. IPM is an interdisciplinary approach that involves pest management principles based on relevant knowledge and practices in agronomy, entomology, plant pathology, nematology, weed science, ecology, horticulture, economics, and systems science (Thill et al. 1991). Despite the heavy reliance on chemicals for weed management in broadacre crop production over the past few decades, weed research has been focusing on alternative approaches and their integration for effective IWM (Jabran and Chauhan 2018). In fact, Oerke (2006) indicated that the higher efficacy of weed management compared with insect pests or disease management was because of the usage of several methods for controlling weeds.

Weeds are the masters of adaptation, hence it is critical to continuously track their evolution in order to better manage them. The focus on studying biology and ecology continues to grow, as it helps better understand shifting weed dynamics and behavior in

Table 3. List of important weed science societies, their specific activities (including conferences/events/meetings, specific journals, educational resources), and their official website links.

Societies	Activities			Websites
	Conferences/meetings	Journals	Educational resources	
Weed Science Society of America (founded in 1956)	Annual meeting (63rd took place in 2023)	*Weed Science, Weed Technology, Invasive Plant Science and Management*	Newsletters, WSSA Book store, Weed Science Webinar Series	https://wssa.net/
European Weed Research Society (founded in 1975)	EWRS Symposium (19th took place in 2022)	*Weed Research*	EWRS Blog, training and workshops on weed science	https://www.ewrs.org/
International Weed Science Society (founded in 1975)	International Weed Science Congress (8th took place in 2022)	—	*Weeds of the South* (book)	https://www.iwss.info/
Asian Pacific Weed Science Society (founded in 1967)	Asian Pacific Weed Science Society Conference (26th took place in 2017)	*Weeds—Journal of the Asian-Pacific Weed Science Society*	APWSS newsletters and conference proceedings	https://www.apwss.org/
Brazilian Weed Science Society (founded in 1963)	Brazilian Weed Science Congress (32nd took place in 2022)	*Weed Control Journal*, *Advances in Weed Science*	Newsletters, blogs	https://www.sbcpd.org/en/
Canadian Weed Science Society (founded in 2002)	Annual meeting (23rd meeting took place in 2022)	*Canadian Journal of Plant Science*	Newsletters, webinars, mobile apps	https://weedscience.ca/
Indian Society of Weed Science (founded in 1968)	Weed Conference/Symposium (29th took place in 2022)	*Indian Journal of Weed Science*	*Weed Science and Management* (book)	https://isws.org.in/
Weed Science Society of Japan (founded in 1975)	Annual meeting (61st took place in 2022)	*Weed Biology and Management*, *Journal of Weed Science and Technology*	Symposium on Plant Protection	http://wssj.jp/
Korean Society of Weed Science (founded in 1981)	2023 spring conference (latest conference took place in 2022)	*Weed and Turfgrass Science*	Special lectures, weed videos	http://www.ksws.kr/
Weed Science Society of China (founded in 1981)	National Weed Science Conference (15th took place in 2021)	—	Newsletters, magazines	http://www.wssc.org.cn/
Weed Science Society of Pakistan (founded in 1987)	National Weed Science Conference (17th took place in 2022)	*Pakistan Journal of Weed Science Research*	Workshop on “Research Priorities in Phyto-Ecology and Weed Management”	https://www.wssp.org.pk/
Turkish Weed Science Society (founded in 1995)	Turkey Herbology Congress (10th took place in 2018	*Turkish Journal of Weed Science*	*Yabancı Otlarla Mücadele* (book)	https://www.turkiyeherboloji.org.tr/
Iranian Society of Weed Science (founded in 2001)	Iranian Weed Science Conference (9th took place in 2021)	*Iranian Journal of Weed Science*		https://isws.areeo.ac.ir/en-US/isws.areeo.ac/33991/page/Home
Weed Science Society of Serbia (founded in 1973)	Congress on Weeds (11th took place in 2021)	*Acta Herbologica*	*Ambrosia* (book), “Weed Resistance to Herbicides” (book chapter)	http://herboloskodrustvo.rs/en/
California Weed Science Society (founded in 1948)	Annual Conference of the California Weed Science Society (75th took place in 2023)	*California Weed Science Society Journal*	*Principles of Weed Control: Weeds of California*, 4th ed. (book)	https://www.cwss.org/
Crop and Weeds Science Society West Bengal (founded in 2004)	CWSC International Conference/Symposium (5th took place in 2019)	*Journal of Crop and Weed*	Seminar symposium, training program, awareness program	https://cwssbckv.org/
The Weed Society of Queensland (founded in 1975)	Pest, Animal and Weed Symposium Proceedings (latest took place in 2019)	—	*Weeds of Southern Queensland*, 4th ed. *Weeds of Central and North Queensland*, 1st ed.	https://www.wsq.org.au/
North Central Weed Science Society (founded in 1997)	Annual meeting (26th took place in 2022)	—	*Interactive Encyclopedia of North American Weeds* (online book)	http://ncwss.org/
Northeastern Weed Science Society (founded in 1947)	Annual meeting (latest was held in 2023)	—	Student writing contests, weed identification and unknown herbicide identification contests	https://www.newss.org/

response to climatic and management factors, ultimately helping in the development of new, improved weed management options (Westwood et al. 2018). Therefore, understanding weed biology and ecology is integral to sustainable weed management, as weed populations adapt and evolve in response to new selective pressures. Another important point to be made about weed

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Table 4. Economic yield losses in selected crops/production systems caused by weed interference.

Crop name	Cost of weeds (per annum)	Country	References
Dry bean (*Phaseolus vulgaris* L.)	US$622 million	United States	Soltani et al. 2018
Dry bean	US$100 million	Canada	Soltani et al. 2018
Maize (*Zea mays* L.)	US$26.7 billion	North America	Soltani et al. 2016
Overall crop production	US$1.658 billion	New Zealand	Saunders et al. 2017
Annual winter crops	AU$1.182 billion	Australia	Jones et al. 2005
Overall grain crops	AU$3.318 billion	Australia	Llewellyn et al. 2016
Rainfed rice (*Oryza sativa* L.)	US$200 million	Africa	Rodenburg et al. 2016
General crops	US$32 billion	Europe	Kubiak et al. 2022
10 major agronomic crops in India	US$11 billion	India	Gharde et al. 2018
7 major crops of Pakistan	PKR 207.41 billion	Pakistan	Shrestha et al. 2021
11 major crops of Bangladesh	BDT 703 million	Bangladesh	Shrestha et al. 2021

management is that all these achievements have been accomplished with relatively few financial resources (Matloob et al. 2020).

Moving forward, weed science has immense scope as a discipline. In the wake of changing climate and mounting food security and food safety concerns around the globe, effectively managing weeds is as important or arguably more important than most other biotic and abiotic production constraints. With many modern digital technologies coming online, weed science could be at the forefront of smart mechanized farming. This presents numerous opportunities for the next generation of weed scientists, farmers, and practitioners, as well as entrepreneurs.

Costs of Weeds

Costs of weeds consist of weed management expenses as well as productivity losses due to weeds (Saunders et al. 2017). Both these factors have a significant impact on the sustainability of productive land usage. Knowledge of the costs of weeds is important for (1) prioritization of key target weed species for research and management; (2) development of cost-effective weed control strategies in the light of benefit-cost analyses; and (3) logical allocation of funding for research, development, and extension (RD&E) in the weed science sector.

Economic yield losses in several crops due to specific weeds in a specific region or country are shown in Table 4. The estimate of the total cost of weeds to New Zealand's agricultural economy was US $1.658 billion (Saunders et al. 2017). In Australia, the financial cost of the 15 most important weeds in 7 agronomic crops was estimated to be AU$1.182 billion per year (Llewellyn et al. 2016). The key parts of this cost were management costs for herbicides, which accounted for AU$571 million, the competitive effects of residual weeds were AU$380 million, and tillage for weed control cost AU$206 million, while weed contamination of grain was a minor cost (AU$25 million) (Jones et al. 2005).

It is important to note that economic and social costs of weeds are often less studied and underestimated due to (1) no concerted effort in the quantification of such losses on large scales, (2) lack of reliable, consistent data, (3) prioritization of funding and resources for developing management tools instead of understanding the actual cost of weed infestations, and (4) limitations surrounding consistent, coherent methodologies and reporting.

Challenges in Weed Science

Weed science was shaped as a specific discipline in the 1950s and has been facing multifarious issues and challenges ever since (Chandrasena 2020). Although it is difficult to generalize challenges and problems facing this discipline across different geographic regions, the themes discussed in this section are frequently encountered and are broadly considered to be the major challenges in the field of weed science.

Lack of Knowledge of Weed Biology and Ecology

A weak understanding of the biology and ecology of weeds hinders the creation of scientifically sound strategies and techniques for weed control. This is mainly because there were previously very few human and financial resources available for fundamental weed research. For example, a large number of weed science organizations have been shut down or reduced in size across Europe in the past few decades (Fernandez-Quintanilla et al. 2008). Until now, only a few European Union projects have specifically addressed weeds, while there are numerous programs targeting plant diseases and insect pests. On the other hand, major developed agricultural nations outside Europe, such as the United States, Canada, and Australia, have started to shift their focus to this area. For example, the Grains Research and Development Corporation (GRDC) in Australia and the U.S. Department of Agriculture–National Institute of Food and Agriculture (USDA-NIFA) have been funding some basic weed science research over the past decade or so. Having said that, RD&E funding for fundamental/foundational aspects of weed biology and ecology is disproportionately limited, hindering progress in this area.

Lack of Technical Knowledge among Farmers about Herbicides

Lack of technical knowledge among farmers about the use of herbicides is one of the major constraints in weed science, especially in developing countries across Asia-Pacific and Africa (Gharde and Singh 2021). Also, there is a dearth of studies about the knowledge and awareness of the safe use of herbicides in those countries. Lack of scientific understanding about herbicides, unawareness of more advanced weed management techniques, and ignorance of safety procedures for herbicide spraying are big obstacles in weed control. Similarly, the intoxication risk for workers with herbicides is high due to a lack of information about the formulation of chemical ingredients in some parts of the world (Machado-Neto 2015). Even in developed countries, issues like non-target damage due to herbicide spray drift are common occurrences. For example, massive dicamba drift/volatilization issues in soybean [*Glycine max* (L.) Merr.]-producing regions of the United States (Sterman and Featherston 2022) and 2,4-D drift to cotton (*Gossypium hirsutum* L.) crops in Australia (Elmore 2023) have created massive socioeconomic problems in recent years. In the 2022 to 2023 season alone, damage to cotton crops

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caused by 2,4-D drift was estimated to be more than AU$100 million in Australia (Bradfield and Felton-Taylor 2023). These environmental and socioeconomic issues surrounding chemical weed control are significant for weed science, requiring robust, on-time RD&E as well as policy development, given that herbicides are still the backbone of any weed management program, especially in broadacre agriculture.

Smaller Trained Workforce in Weed Science

Unlike other crop protection disciplines, such as plant pathology and entomology, far fewer departments in agricultural institutions are entirely focused on weed science (Chauhan et al. 2017). Furthermore, very few university educators/researchers are charged with managing weeds in pastures, ornamental, aquatic, and forest environments. Additionally, degree-awarding institutions from different regions of a nation, particularly in developing nations, have nearly uniform weed science curricula that do not consider regional variations in crops and weed species, cropping systems, input levels, management practices, socioeconomic backgrounds, and farmer skill levels for managing weeds. Agricultural education, research, and farming are seeing a significant decline in interest from youth, which translates into and multiplies the problems for a small discipline like weed science.

The Absence of Proper Funding

Research efforts for studying and controlling weeds, which are both resource and time intensive, appear less appealing to funding organizations. With the exception of a few short-term bioassay studies, research on weed biology in the context of climate change is progressing slowly, particularly in terms of long-term, system-based trials. Such comprehensive studies necessitate an interdisciplinary approach due to their complex and time-consuming nature and therefore require significant funding, resources, and collaboration. Improper delivery of information is also a major weakness, because the knowledge becomes useless if it is not properly delivered to users (Coble 1994). Not many countries have well-established, integrated extension and outreach programs facilitating problem-oriented research and real-time knowledge dissemination. There are very few successful examples of RD&E networks, organizations, or collaborations delivering pragmatic weed management outcomes across the globe. A coordinated network and public–private sector partnership for improved grains RD&E including weed management through GRDC in Australia is a good framework; however, funding is still highly competitive, and weed science gets a smaller portion. In the United States, established weed science programs at most land-grant universities and USDA–Agricultural Research Services (USDA-ARS) laboratories and increasing collaboration among researchers and industry are good models to follow for improved research outcomes and stewardship and expedited adoption of new weed management technologies/programs.

Overall, the absence of proper funding for state weed science programs is a significant barrier to building the type of research program needed in weed science. Burnside (1993) described weed science as a stepchild due to the decline in research efforts and neglect of this discipline. The cuts in the funding of weed science projects appear to be inconsistent with the need, especially in Europe and the United Kingdom. There were as few as 10 principal investigators involved in full-time publicly funded weed research programs in England a few years ago (Froud-Williams 2017).

Another problem is the lack of weed specialists and organizations directly advocating for weed science–related policy development and funding. Historically, weed science has been underrepresented in broader crop-, plant-, ecology-, and biosecurity-related professional societies, forums, and think tanks. Dedicated funding streams for weed science and better advocacy for this cause are necessary.

Challenging Job Market

Weed science has conventionally experienced the "new kid in town" syndrome (Fernandez-Quintanilla et al. 2008). It has mostly come late to several new concepts evolving in plant protection: ecology and agroecology, IPM, habitat management, herbicide-resistant crops, and biodiversity in agroecosystems. This is due to weed science being a relatively young discipline, its low specific weight, and the fact that several other niches were already filled when this discipline emerged. So, due to these niches, it becomes difficult to create a separate job market for weed scientists. Also, many pesticide companies hire nontechnical staff to sell their products related to weed management. This is another big reason for fewer job being available.

Research and education-based jobs have been historically limited in weed science. Such job opportunities in weed science are scattered, and there is huge geographic inequality. For example, weed science graduates in the United States can find relevant jobs easily in academia, industry, and government sectors, while those outside North America have a really difficult time. As a matter of fact, in just the last 3 years, more than 20 faculty positions specifically in weed science were advertised across the United States (https://wssa.net/category/jobs), while that number was probably less than 5 outside the United States. In addition, weed scientists often have to compete with experts in allied fields which is not the case with relatively bigger crop protection fields/disciplines like entomology and plant pathology.

Herbicide-Resistance Challenges

Heavy reliance on synthetic herbicides, constant use of herbicides with a single mode of action, and herbicide applications at inaccurate doses have caused widespread evolution of herbicide resistance in weed populations across the world (Heap 2023; Torra et al. 2021). Herbicide resistance has become the greatest concern of weed science in recent times, because it ultimately threatens profitable crop production and food security. It has increased the costs of crop production, especially in developed nations that largely depend on herbicides to grow highly productive herbicide-tolerant crops (Burke and Bell 2014). Weed species belonging to *Amaranthus*, *Lolium*, *Conyza*, and *Echinochloa* genera are the worst herbicide-resistant weeds, with proven capabilities of evolving resistance to a wide range of sites of action (Heap 2014). Also, recent studies of multiple and cross-resistance to several herbicides have increased concern, as there are fewer herbicide options for certain weed species (Peterson et al. 2018). Effective management of herbicide-resistant weeds requires cutting-edge research, coordinated education, and continuous outreach efforts. Herbicide-resistant weeds also require new management strategies that are not solely reliant on herbicides.

Challenges to the Adoption of Modern Technologies

Modern digital technologies offer great opportunities for agronomic operations, including weed management (Bajwa et al. 2015).

However, one of the major challenges in using modern technologies such as robotics for weed management is identifying different weed species accurately (Slaughter et al. 2008). Weeds can have different shapes, sizes, and colors, and detecting them can be challenging, especially in complex and dynamic environments like agricultural fields. Robotic systems need to be designed to work in a range of environments and conditions, including different crop types, soil types, and weather conditions. They must also be adaptable to different weed densities and distributions. Data management is another problem, as the amount of data generated by robotic systems can be overwhelming. The data must be stored, processed, and analyzed to provide meaningful information for decision making.

The development and implementation of robotic systems can be expensive. The high costs associated with the development of custom robotics platforms and sensors may be a barrier for some farmers and researchers. The use of robotics in agriculture may be subject to legal and regulatory barriers. For example, the use of drones for crop monitoring and pesticide application may be subject to strict regulations, including registration and certification requirements. This can be a complex task, and integrating robotics with legacy equipment can be particularly challenging.

Prospects for Weed Science

Although several leading universities offer education and training in weed science directly or through courses embedded in their crop science–related degrees, the overall number of educational providers within this important discipline is very small on a global scale, especially in underdeveloped countries. The study of basic and fundamental principles of weed science should be compulsory for agriculture students. Weed science students should seek knowledge of weed biology, ecology, and IWM, along with advanced technologies such as remote sensing, artificial intelligence, computing, and robotics. This will diversify students' skills within weed science while potentially broadening job opportunities for them in agricultural engineering and industry.

Climate change is one of the world's major challenges (and an opportunity as well), and it will become even more critical for agriculture and weed science in the near future given the increasing global population and food demand. Unfortunately, crop protection as well as weed invasions and weed management will become more difficult under future climatic conditions (Bajwa et al. 2020, 2021; Jabran et al. 2020). Weed scientists have a key role to play in both mitigation of and adaptation to adverse effects of climate change through more adaptive research using complex climate change scenarios. This might be implemented by reducing tillage practices and avoiding flaming and encouraging conservation tillage practices, site-specific weed management, reduced herbicide rates, and biological and cultural control (Somasundaram et al. 2020). In addressing climate change, the disciplines of weed science and invasion ecology can learn a lot from each other, and there are certain principles and practices that can be exchanged and mutually applied to achieve sustainable outcomes (Sun et al. 2021).

To be effective, weed management strategies must take into account weed ecology in connection to environmental, genetic, and biochemical factors, as well as and molecular biology information. The use of genetic techniques can help to identify and characterize genes that are involved in weed growth and development. This research can lead to the development of new herbicides that target specific genes in weeds, making them more susceptible to management options while reducing their negative impacts. Also, by using techniques such as gene editing and RNA interference, researchers can modify the genetic makeup of weeds to make them more susceptible to herbicides or even to cause them to self-destruct. The economics of both weed-induced production losses and weed control techniques must be taken into consideration when creating an adequate weed science curriculum.

Weed science is an integrative scientific discipline that combines both applied and basic sciences to understand and effectively manage some of the most undesirable plants in agroecosystems. The work of weed scientists is challenging, and several advances have been achieved, including achieving scale as a specific discipline. Still, numerous issues have yet to be fully explored, including the role of molecular biologists, invasion ecologists, and plant physiologists in basic and applied research for vegetation management in agricultural and nonagricultural ecosystems.

In the future, weed science as a discipline needs to be described in more precise and positive ways to attract potential students. Additionally, multidisciplinary weed science needs to be developed or introduced so that students can learn more about the complexity of weeds in farming systems and then go on to find innovative solutions. Topics such as molecular analysis of suspected herbicide-resistant weeds, weed management by genetic tools like RNAi, and weed identification by DNA barcoding and sequencing need to be incorporated into coursework for weed science students. Also, there is a need for cooperation between government organizations and private industry for the creation of internship/placement programs for weed science graduate students.

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