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Herbicides vis-à-vis other pesticides: Trend analysis and economic impact

ICAR-Directorate of Weed Research
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Crop yield losses due to various pests in India

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Foreword

Weeds are the most serious and pervasive biological barrier to agricultural production, with crop yield loss due to weeds in India estimated to be around US$ 11 billion per year in ten major field crops. However, many developing countries including India faces the problem of labour shortage for manual weeding as millions of people migrate from rural to urban areas. Herbicides are much more affordable and accessible now a days than manual hand weeding. Accordingly, farmers' adoption of herbicides scaled up considerably in the recent past particularly in advanced countries like USA, Germany, Japan, etc.

Herbicides constitute more than half of the crop protection market globally followed by fungicides and insecticides, whereas in India, the share of herbicides is quite low (17%) compared to insecticides (44%) and fungicides (37%). However, it is interesting to note that use of herbicides in India is increasing at a much faster rate (15-20%) in the past one decade. In this context, understanding the production, consumption, and demand trend of herbicides in comparison with other pesticides has great significance. There is a need to have long-term time series data to analyze the supply-demand gap of herbicides and other pesticides in different crops and agro-ecological regions of the country. Further, it is very important to have an estimation of the economic benefits that farmers obtained due to the herbicide use in various crops.

The present publication entitled "Herbicides vis-à-vis other pesticides: Trend analysis and economic impact" is a compilation of research works based on secondary data on herbicides and other pesticides that are being used in Indian agriculture. I am sure that this publication would be helpful to researchers, policymakers, and other stakeholders. I congratulate the authors for bringing out this publication in the form of a technical bulletin.

(S.K. Chaudhari)

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Preface

Weeds are major biotic stressors and notorious yield reducers that are economically more harmful than insect pests, diseases,or other crop pests. If weed growth is not stopped at a critical stage of crops, it results in massive crop loss, sometimes as high as complete crop failure. Being a botanical pest, its adaptability to the cropping system and damage potential is significantly high. Before the introduction of selective herbicides, a combination of cultural tactics like crop rotation, cover crop, fallow, proper tillage, etc. was used to manage the weed problems in crops. Considering the drudgery, increasing wages and non-availability of human labour for manual weed management in agriculture, extensive research has been conducted around the world on alternative methods. The late 1940s witnessed the introduction of selective herbicides, and subsequently, several new herbicides have been developed and this provided a new tool for weed management. The contribution of herbicides along with other pesticides was very crucial in the success of the green revolution, particularly in developing countries in Asia. India has traditionally relied heavily on hand weeding for weed management. However, cost-effective measures i.e. herbicides became more popular as agricultural labour became more expensive and scarce. Herbicides selectively eliminate weeds and assist crops to grow more effectively.

Herbicide use in Indian agriculture is not well-documented, and there is no systematic time series data on its production, consumption, and demand. Furthermore, pesticide/herbicide industry is mainly controlled by multinational private companies and therefore, such data records are difficult to access. The present publication mainly focused on the trend analysis of production, consumption, and demand of herbicides vis-à-vis other pesticides in India and an economic impact case study of herbicide use in selected crops. We relied on secondary data obtained from the Directorate of Plant Protection, Quarantine & Storage, Ministry of Agriculture and Farmers' Welfare, Government of India, and State Agricultural Department offices for the study. This technical bulletin also contains some compiled information on yield loss due to biotic stresses, classification of pesticides, herbicide resistance, etc.

We would like to extend our sincere gratitude to Mr. Sandeep Dhagat, Chief Technical Officer and Mr. SK Pare, Sr. Technical Officer for their help in collection of secondary data and the preparation of this publication. Thanks are also due to State Government Agencies and pesticide dealers for providing the necessary information. We hope that this technical bulletin will help the readers to understand where herbicides stand in relation to other pesticides and what are the leading herbicides in India and their economic impacts.

Date: 14-02-2023

Authors

CONTENT

I. Introduction

Agriculture plays significant role in the economy and impacts society in many ways. However, there have been a lot more pests targeting major crops (FICCI 2015). The UN Food and Agriculture Organization (FAO) estimated that insects, weeds, and diseases destroy about 40 percent of crops in developing countries. In India, around 35 to 45 percent of crop yield is lost to diseases, insects, and weeds, while 35 percent of crop products are lost during storage (OPCI, Outlook of Pesticide Consumption in India, 2014). Thus, food security is seriously threatened by the growing crop losses caused by pest damage, which highlights the significance of agrochemicals. Like all other inputs, pesticides are essential to increase agricultural production. The conventional approaches to plant protection for controlling insect pests, diseases, and weeds have been eclipsed by the rising use of synthetic pesticides in agriculture (Sharma *et al*., 2018). Further, pre- and post-harvest losses, which have become more important in recent years in agriculture, must be prevented with pesticides. As per an estimate, globally more than half of the pesticides are utilized in Asia and India stands 12^{th} in pesticide use globally and 3^{rd} in Asia after China and Turkey (Nayak and Solanki, 2021). In India, the usage of pesticides has increased due to the rise in demand for agricultural products and the subsequent commercialization of agriculture. The shift of agriculture management strategies to the mode of agribusiness laid emphasis on risk management as one of the major challenges in agriculture (Devi *et al*. 2017). Further, among various pesticide groups, herbicides share a major chunk in terms of consumption as well as production.

The growing global population and rising food demand have made it difficult to predict whether our agricultural output will be able to supply enough food in the future (Basu and Rao, 2020). Weed interference is one of the major obstacles that lowers crop yield and, consequently overall food production (Soloneski, 2013). Weeds are undesired plant species that are tenacious and impede the growth of other crop plants. By competing with crops for environmental resources like water, light, and nutrients, they can reduce crop yield annually and cause billions of dollars in global crop losses (Meena, 2015). Additionally, they have an impact on the nation's economy, agricultural progress, and natural processes. Therefore, since the beginning of agriculture, weed management has been a significant concern for crop farmers. A long-term strategy is necessary for helping to anticipate and prevent future weed issues and thereby maintaining agricultural productivity (Ahmed *et al*. 2010; Verma, 2014). Crop yield loss due to weeds in India is estimated at about US$11 billion every year (Gharde *et al*. 2018). If the farmer does not manage the weed growth at the critical stage, it may cause crop loss as high as 70%. A study conducted on 10 major crops revealed these frightening statistics. Weeds not only yield reducers but, in many instances, are economically more harmful than insects, fungi, or other crop pests. The introduction of selective herbicides in the late 1940s and the subsequent discovery of new herbicide molecules provided a wonderful tool of weed management to farmers called “Chemical hoe” (Kudsk and Streibig, 2003). Herbicides are continued to be one of the most effective and easiest tools for weed management in Indian agriculture.

Throughout the world, herbicides have been used for a very long time. The "chemical era" for the creation of herbicides began with World War II. Herbicide usage is expanding over the years. The migration of millions of people from rural to urban regions has resulted in a labour shortage in several developing nations, including Bangladesh, China, India, and others (Gianessi, 2013). Herbicides are a much more cost-effective and accessible alternative to hand weeding in these nations and therefore, the use of herbicides accounts for 44% of all agrochemicals globally and 30% in India (Sondhia, 2014). When manual weeding appears difficult or impossible, they can quickly eradicate weeds in critical circumstances. Herbicides eliminate weeds, assisting crops in growing more effectively and protecting them from the negative consequences of weeds, such as competition for resources, release of toxins, alteration of the microbial population in the soil and the air, harbouring of pests, etc. (Maheswari and Ramesh, 2019). Nevertheless, soil and climate change have a significant impact on the safety and efficacy of herbicides (Robinson, 2019). In most cases, one application is sufficient, however practising repeated application can also be useful. These plant poisons are not particularly dangerous to animals, but by altering the flora of the treated site, they have an indirect impact on animal and microbial habitat (Busse *et al*. 2001). Improper use of herbicide also taints groundwater and surface water, including ponds, streams, rivers, and lakes (Meena *et al*. 2020). As their concentration rises over time, the toxic herbicides gradually contaminate the food chain.

India has diverse agro-climatic situations across the country. Different kinds of weed problems affect incredibly diverse farming and agricultural systems. They require constant monitoring and effort in many environments because of their dynamic nature (Rao, 2018). India has traditionally relied heavily on hand weeding for weed management. But when agricultural labour became more scarce and expensive, cost-cutting measures like herbicides (Rao *et al*. 2015), notably chemical herbicides, became more prevalent. Herbicide use grew three times between 2006 and 2016, while area used for cultivation did not change in that same proportion (Choudhury *et al*. 2016). Low-dose high potency newer generation herbicides are also replacing traditional high dose compounds in use. With this backdrop, the present study attempted to find out the growth trend and pattern of herbicide consumption vis-à-vis other pesticides in India, herbicide usage in major crops and economic benefit accrued due to herbicide use in central India.

2. Herbicides vis-à-vis other pesticides: Global and Indian scenario

Pesticide usage patterns in India differ from those worldwide (Figure 1). In India, 293 pesticides were registered, and it was reported that 104 pesticides are still manufactured or used despite being banned in two or more other countries (GoI, 2021). Insecticides accounted major share (51%) of total pesticides used in India whereas herbicides recorded the highest share (53%) in the world. As per the 2020 data, the pattern of use of pesticide in India is insecticides>fungicides>herbicides>other pesticides whereas, the global pattern is herbicides>fungicides>insecticides>other pesticides. One decade ago, the pesticide use pattern in the world and India was similar, though the percentage share was different. In 2009, the highest share in the world and India was recorded by insecticides with respective shares of 44% and 76%, whereas herbicides was at second postion (30%) in the world and 3rd highest share (10%) in India (Aktar *et al*. 2009). The trap of decreased skill, exacerbated insect problems, and increased spraying has played a significant role in India becoming a global outlier in insecticide use (Stone and Flachs, 2018). Out of the total insecticides used for pest management in India, around 50 per cent are diverted to cotton pest management (Aktar *et al*. 2009; Mooventhan *et al*. 2020). The global pesticides market reached a value of US$ 83.9 billion in 2021 and the market is to reach US$ 111.4 billion by 2027 according to the forecast of IMARC Group, exhibiting a CAGR of 4.34 per cent during 2022-2027. The herbicides segment dominated the global market (Figure 2) as many developing countries, such as India and China, face shortage of labourers for manual weeding. In the upcoming years, the market segment growth is anticipated to be supported by the high efficiency that herbicides offer over manual weeding techniques. The introduction of various herbicide products with distinctive qualities based on the selectivity of weeds and the emergence of crops provides additional support for market expansion. On the other hand, the expansion of the use of genetically modified crops in various regions has led to a rise in the use of herbicides in crop production (www.fortunebusinessinsights.com). The Indian pesticides market worth around Rs. 212 billion in 2021 and the IMARC Group projected that the market will reach INR 320 billion by 2027, with a CAGR of 7.07 per cent during 2022 to 2027.

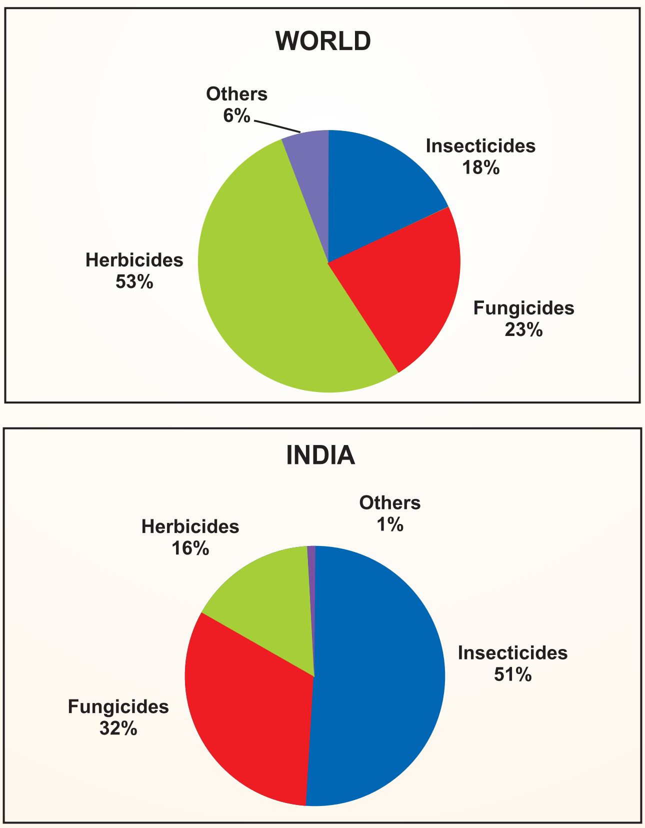

Fig 1: Pesticide use in world and India in 2020

(Source: https://www.fao.org/faostat/en/#data/RP)

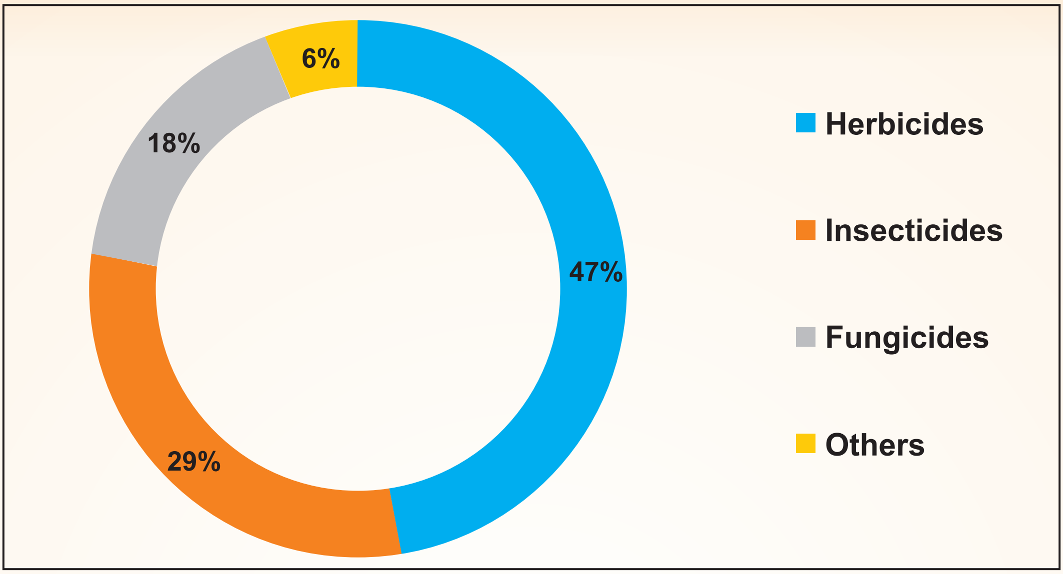

Fig 2: Global crop protection chemicals market share by types in 2020
(Source: www.fortunebusinessinsights.com)

3. Biotic stress and yield loss due to weeds in crops

Living organisms, such as viruses, bacteria, fungi, nematodes, insects, arachnids, and weeds cause biotic stress in plants. Biotic stress is a major cause of pre- and post-harvest losses in agriculture. The most serious and pervasive biological constraint on agricultural production is weed, which harm both cropped and non-cropped areas. Besides increasing production costs, they decrease crop yield and deteriorate produce quality. Weeds also pose a threat to human health and reduce biodiversity in uncultivated areas. According to estimates, weeds alone account for nearly 37 per cent of the losses brought on by agricultural pests (Figure 3). Weeds are more common and have an impact on practically every circumstance than other pests. There are regional differences in the biology and ecology of weeds. Soil, climate, crop, and management characteristics all have an impact on the composition, distribution, and competition of weeds. Weeds appear to be much more adapted to agro-ecosystem than crop plants. They compete directly with the crop plants for the available resources such as moisture, nutrients, light and space, and indirectly through exudation/production of allelochemicals. One of the major principles of crop-weed competition is that the plants established in the soil earlier try to smother other species of plants coming at later stages. The emergence of weeds begins simultaneously with the crop leading to severe competition between weeds and the crop right from the very early stage. In the rainy season, weeds emerge in succession almost throughout the crop season. The critical period defines the maximum period weeds can be tolerated without affecting final crop yields (Frantík *et al*. 1987). This provides information on the active duration when weeds make a deleterious effect on crops. The initial one-third part of the life of the crop is critical where the maximum competition takes place and suffers maximum and irreversible losses (Table 1). Yield loss largely depends on the species and their densities prevailing at the site. Considering all these factors, it is necessary to have location-specific weed management practices that cope with the agro-ecological conditions so as to have more effective control. Farmers often disregard weeds for a variety of reasons, even during the critical crop-weed competition phase. It is crucial to raise awareness of the losses caused by weeds and the need for better weed management technology in order to increase crop output.

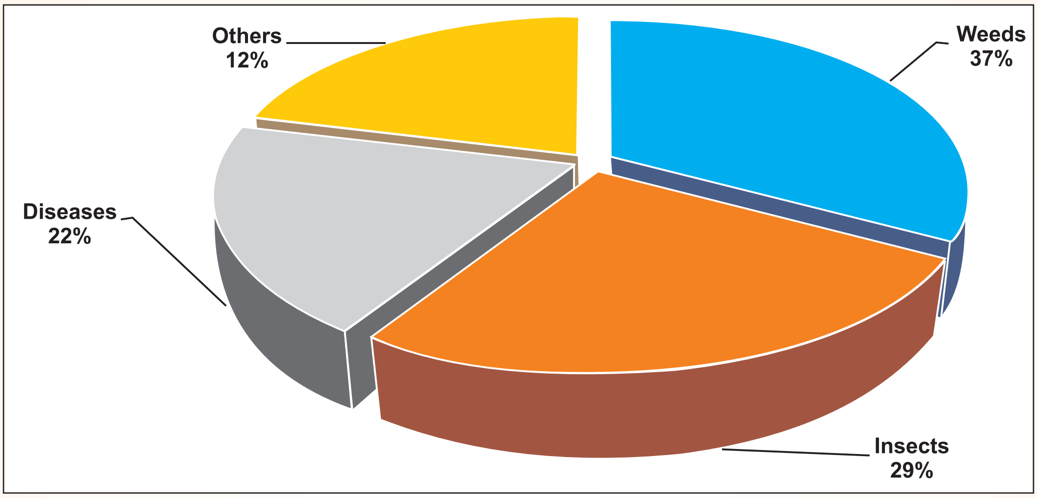

Fig. 3: Crop yield losses due to various pests in India (Source: ICAR-DWR, Jabalpur)

Table 1. Yield loss due to weeds in major crops grown in India

Crops	Yield loss (%)	References
Cereals		
Rice	32-95	Choudhary *et al.*(2021)
Maize	32.4-42.3	Sharma *et al.*(2000)
Wheat	45.5-63.9	Reddy and Reddy (2002)
Pearlmillet	55	Banga *et al.*(2000)
Sorghum	15-97	Mishra *et al.*(2012)
Minor millets	30-55	Anonymous (2021)
Pulses		
Greengram	65.4-79	Dungarwal *et al.*(2003)

Table contd...

Pigeonpea	20-40	Mishra (1997)
Cowpea	30-50	Mishra (1997)
Lentil	Up to 80	Mohamad *et al.*(1997)
Chickpea	22-100	Poonia and Pithia (2013)
Clusterbean	53.7	Saxena *et al.*(2004)
Oilseeds		
Soybean	74	Chhokar and Balyan (1999)
Sunflower	54.6	Wanjari *et al.*(2001)
Groundnut	15-75	Priya *et al.*(2013)
Mustard	10-58	Banga and Yadav (2001)
Sesame	15-40	Mishra (1997)
Caster	30-35	Mishra (1997)
Safflower	35-60	Mishra (1997)
Linseed	30-40	Mishra (1997)

4. Major classification of pesticides

Pesticides can be classified based on their origin, compound, and target organisms. They are classified into natural pesticides and synthetic pesticides based on their origin. Natural pesticides are those that are isolated from natural sources like plants or microbes. These pesticides are biodegradable and non-toxic to mammals (Campos *et al*. 2016). The most widely used natural pesticides are nicotine, neem, pyrethrum, and rotenone (Duke *et al*. 2010). Synthetic pesticides on the other hand are man-made compounds produced by altering minerals or chemical substances. These pesticides are the ones that are most commonly used all over the world. Organochlorines, organophosphates, pyrethroids, and carbamates are a few examples of such synthetic pesticides that have been shown to be extremely stable in nature and accumulate over time. (Jayaraj *et al*. 2016).

On the basis of the compounds, synthetic pesticides can be further divided into organic and inorganic compound pesticides. Organic compound pesticides are formed by controlling the structure of the organic compound. These pesticides are considered the most potent ones and block the important processes of the central nervous system of the target organisms (Abreu-Villaca and Levin, 2017). Whereas, inorganic compound pesticides are created by altering the inorganic substances. Some of the pesticides in this category are arsenic, copper, boric acid, silicates, and sulphur (Gimeno-Garcia *et al*. 1996). Studies suggested restricting the use of these kinds of pesticides due to very high levels of contamination and environmental harm (Shaban *et al*. 2016). Another important classification of pesticides is based on the target organisms (Table 2). Each pesticide is designed to target a specific pest such as weeds, insects, fungi, rodents, etc.

Table 2. Classification of pesticides on the basis of target organisms along with examples

Name	Target organism	Uses	Examples
Acaricide	Mites and ticks	Used to kill ticks and mites around homes	DDT, Dicofol, organophosphates, Carbamate
Avicide	Birds	To control birds in orchards	Strychnine, Fenthion
Algicide	Algae	For removal of algal growth from water reservoirs such as swimming pools and lakes	Benzalkonium chloride, Copper sulphate, Dichlone, Simazine
Bactericide	Bacteria	As disinfectants,antiseptics and antibiotics	Quaternary ammonium compounds, Silver nitrate, Mercury chloride, Hypochlorites, Triclosan, Hexachlorophene
Fungicide	Fungi	In preventing plant diseases	Tea tree oil, Cymoxanil, aureofungin, Metalaxyl, Hexaconazole
Herbicide	Weeds	for removing weeds	Atrazine, Paraquat, Oxadiazon, Glyphosate, Metoxuron, Sulfosulfuron, Linuron
Insecticide	Insects	Used to kill insect eggs and larvae	Azadirachtin, Malathion, Carbofuran, Chlorfenapyr, DDT, Lindane, Endosulfan, Thiamethoxam
Molluscicide	Molluscs	Used for agriculture and gardening	Metaldehyde, Thiacloprid
Nematicide	Nematodes	As fumigant for crops	Chlorpyrifos, Phosphamidon, methyl bromide, Fenamiphos
Rodenticide	Rats	Managing invasive rodents	Zinc phosphide, Bromadiolone, Coumachlor, Coumatetralyl, Warfarin
Synergists	Several pests	Act to increase the toXicity of other pesticides	Piperonyl butoXide
Virucide	Viruses	To control the spread of viruses	Cyanovirin-N

Source: Sharma *et al.* 2020

4.1. Classification of herbicides

Plenty of herbicides with different chemical content and various modes of action were developed since 1970s. This necessitated the creation of a system to keep these products organized so that proper herbicide selection, easy diagnosis of herbicide injury symptoms, strategies for managing resistance, and mode and timing of applications would be possible. Accordingly, herbicides were classified based on the time of application viz. pre-plant, pre-emergence, and post-emergence. Also, they were classified by their method of application, viz. foliar or root absorbed; selective or non-selective; and contact or systemic. Herbicides were classified into various chemical groups, such as amides, phenoxyalkanoic acid, triazines, ureas, sulfonylureas, imidazolinones, etc., from a chemistry perspective. However, the classification made by the Herbicide Resistance Action Committee (HRAC) based on the modes of action of herbicides was found most effective method (Table 3). Instead of basing decisions on product names, the system looked at how an herbicide affected a plant. With the help of this system, herbicides can be chosen correctly, resistance can be managed, and herbicide injury symptoms can be diagnosed more quickly.

Table 3. HRAC Classification of herbicides based on their site of action

Site of action	Chemical family	Active ingredient
Inhibition of acetyl CoA carboxylase (ACCase)	Aryloxyphenoxy propionate Cyclohexanedione	Fenoxaprop, Fluazifop, Quizalofop Clethodim, Sethoxydim
Inhibition of acetolactate synthase (ALS)	Sulfonylurea	Chlorimuron, Chlorsulfuron, Foramsulfuron, Halosulfuron, Iodosulfuron, Nicosulfuron, Primisulfuron, Prosulfuron, Rimsulfuron, Sulfometuron, Thifensulfuron, Tribenuron
	Imidazolinone Triazolopyrimidine	Imazamox, Imazapyr, Imazaquin, Imazethapyr, Flumetsulam, Cloransulam
Inhibition of microtubule assembly	Dinitroaniline	Benefin, Ethalfluralin, Pendimethalin, Trifluralin
Inhibition of indole acetic acid transport	Phenoxy	2,4-D, MCPA, MCPP
	Benzoic acid	Dicamba
	Carboxylic acid	Clopyralid, Fluroxypyr, Picloram, Triclopyr
	Semicarbazone	Diflufenzopyr
Inhibition of photosynthesis at photosystem II site A	Triazine	Atrazine, Ametryn, Prometon, Simazine
	Triazinone	Hexazinone, Metribuzin
	Uracil	Bromacil, Terbacil
Inhibition of photosynthesis at photosystem II site B	Nitrile	Bromoxynil
	Benzothiadiazole	Bentazon
Inhibition of photosynthesis at photosystem II site A-different binding behavior	Urea	Diuron, Linuron, Tebuthiuron

Table contd...

Photosystem I-electron diversion	Bipyridilium	Paraquat, Diquat
Inhibition of EPSP synthase	None accepted	Glyphosate
Inhibition of glutamine synthetase	None accepted	Glufosinate
Inhibition of lipid biosynthesis - not ACCase inhibition	Thiocarbamate	Butylate, EPTC
Bleaching: Inhibition of DOXP synthase	Isoxazolidinone	Clomazone
Bleaching: Inhibition of 4-HPPD	Isoxazole	Isoxaflutole
	Triketone	Mesotrione, Sulcotrione
	Pyrazolone	Topramezone
Inhibition of protoporphyrinogen oxidase (Protox or PPO)	Diphenylether	Acifluorfen, Fomesafen, Lactofen
	N-Phenylphthalimide	Flumiclorac, Flumioxazin
	Aryl triazinone	Sulfentrazone, Carfentrazone
Inhibition of synthesis of very-long-chain fatty acids (VLCFA)	Chloroacetamide	Acetochlor, Alachlor, Metolachlor, s-Metolachlor, Dimethenamid
	Oxyacetamide	Flufenacet
Source: Choudhury *et al*. 2016		

5. Herbicides vis-à-vis other pesticides: Trend analysis of production, consumption and demand

To find out the growth trend and pattern of production, consumption, and demand of herbicides vis-à-vis other pesticides in India, secondary data published by the Directorate of Plant Protection, Quarantine & Storage, Ministry of Agriculture and Farmers' Welfare, Government of India was used. Different charts and diagrams were used to depict the results more coherently. The compound annual growth rates (CAGR) of herbicide and other pesticides production, consumption, and demand were estimated by exponential function as it has the advantage of taking all the data points into consideration. The compound growth function is specified in the following form.

$$y_t = ab^t e^u \text{ -------------- } (1)$$

Where,

y_t = Production/consumption/demand of herbicides or other pesticides in the year t

t = time period

a = intercept value (value of y when t = 0)

b = (1+r), 'r' being the growth rate

e = error term

Equation (1) was converted into the logarithmic form in order to facilitate the use of linear regression. Taking logarithms on both sides we obtain,

$Ln\ y_t = Ln\ a + t\ Ln\ b + u$ ---------------(2)

Ln a and Ln b are obtained by applying ordinary least squares (OLS) procedure to equation (2) and the growth rate 'r' is computed as below:

r = (Anti Ln of b - 1) X 100 -----------(3)

5.I. Production trends and patterns of various pesticide groups in India

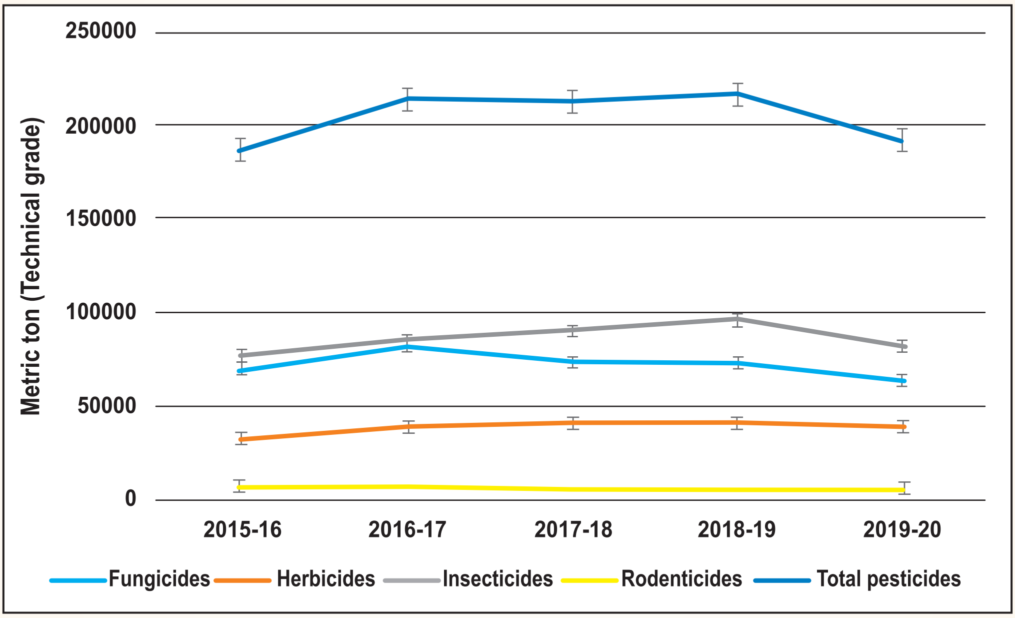

Fig. 4: Production trend of different pesticide groups over the years

(Data source: https://ppqs.gov.in/statistics)

The production volume of different groups of pesticides in India for the five years ending in 2019-20 indicated an increasing trend altogether (Figure 4). The total pesticide production has increased from 188 thousand MT in 2015-16 to 192 thousand metric tons (MT) in 2019-20. However, the highest production (217 thousand MT) was observed in 2018-19. It was on increasing trend till 2018-19 and showed decline of 25 thousand MT in 2019-20 as compared to the previous year. Production volume of herbicides also indicated the similar trend during this period. It was 33 thousand MT in 2015-16 and reached to 39 thousand MT in 2019-20. Highest production (42 thousand MT) was observed in both 2017-18 and 2018-19. A dip of 3 thousand MT was recorded in 2019-20 as compared to the previous year. The perusal of table 4 revealed the compound annual growth rates (CAGR) of the production of various pesticides. Total pesticide production in the country depicted a compound annual growth rate of 0.59 per cent during 2015-16 to 2019-20. Out of which, production of herbicides topped with 4.39 per cent followed by insecticide with 2.49 per cent. Whereas, fungicides and rodenticides showed negative growth rate of -3.00 per cent and -5.12 per cent, respectively. Furthermore, the dip in total pesticide production observed in 2019-20 is attributed to the decreased production of fungicides and insecticides. Banning of various pesticide molecules in recent past could be the reason for registering the declined production. Figure 5 depicted percent share of different pesticide group in total production of pesticides for the year 2019-20. Insecticides occupied the top position with more than 40 per cent followed by fungicides with more than 30 percent and herbicides with more than 20 per cent share.

Table 4. Compound annual growth rate of production of different pesticides

S.N.	Pesticide Group	CAGR (%)
1	Fungicides	-3.00
2	Herbicides	4.39
3	Insecticides	2.49
4	Rodenticides	-5.12
5	Total pesticides	0.59

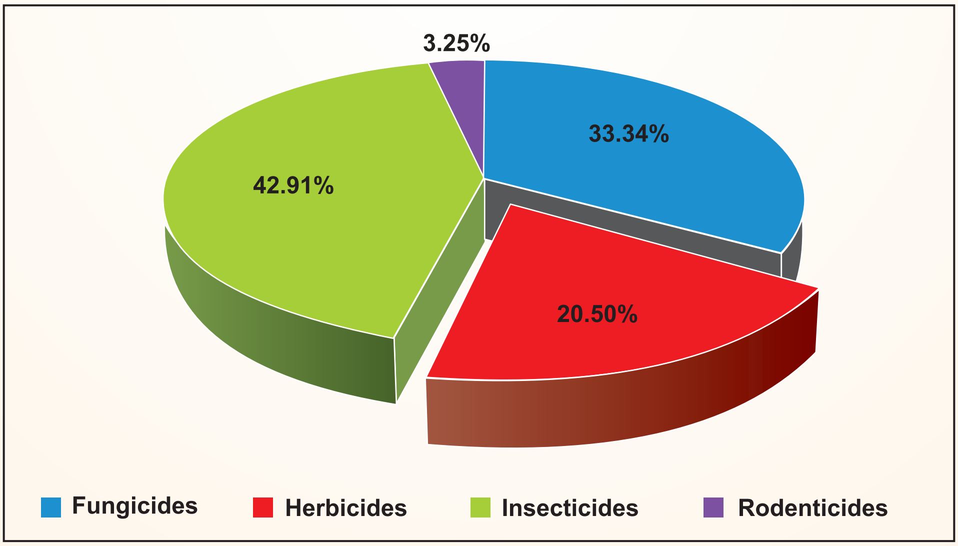

Fig. 5: Per cent share of different pesticide groups in total pesticides production in 2019-20

(Data source: https://ppqs.gov.in/statistics)

5.2. Production trends and patterns of herbicides in India

The production volume of herbicides in India altogether depicted an increasing trend over the years (Figure 6). Among the 6 key herbicides, 2,4-D recorded the highest volume of production over the years. It was recorded 18 thousand MT in 2015-16 and 22 thousand MT in 2019-20. However, the peak production of 2,4-D was in 2017-18 (25 thousand MT). Glyphosate occupies the second position in production with 6.9 thousand MT in 2015-16 and 5.9 thousand MT in 2019-20. Except for glyphosate, all other key herbicides recorded an increasing trend in production volume in 2019-20 as compared to production in 2015-16. Glyphosate depicted a decreasing trend in production over the years. In terms of compound annual growth rate, all six key herbicides together recorded 5.71 per cent during 2015-16 to 2019-20 (Table 5). Barring glyphosate, all other herbicides showed a positive growth rate of production during this period. Of the six key herbicides, metribuzin registered the highest growth rate (30.72%) followed by diuron (21.74%) and pretilachlor (13.36%). Year-wise percent share of key herbicides in total herbicides production was depicted in figure 7. It was indicated that 2,4-D consistently had nearly 60 per cent share all the years and it declined to 57 per cent in 2019-20. The second highest share was recorded by glyphosate, but the per cent share showed a decreasing trend over the years. It was 23 per cent in 2015-16 and reached 15 per cent in 2019-20. Though the herbicide had highest growth rate, its contribution in terms of per cent share was very meagre. All the years, metribuzin showed a less than 10 per cent share and it was highest in 2019-20 (7%). Atrazine depicted an almost constant share all the years (4-5%) and diuron showed an increasing contribution over the years in the total production of herbicides.

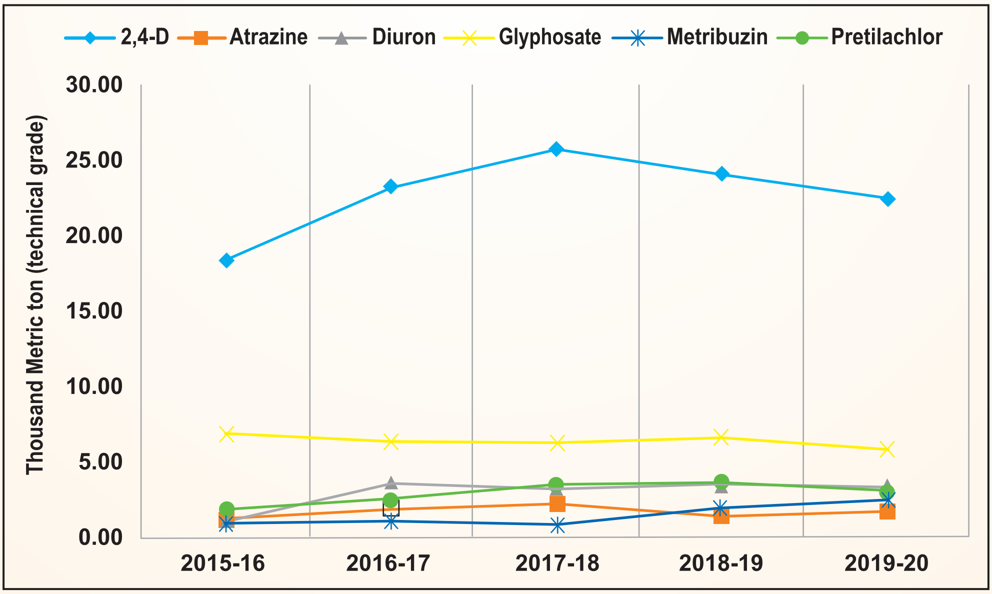

Fig. 6: Production trend of key herbicides in India
(Data source: https://ppqs.gov.in/statistics)

Table 5. Compound annual growth rate of production of key herbicides

S.N.	Herbicides	CAGR (%)
1	2,4-D	4.48
2	Atrazine	4.77
3	Diuron	21.74
4	Glyphosate	-2.72
5	Metribuzin	30.72
6	Pretila chlor	13.36
7	Total herbicides	5.71

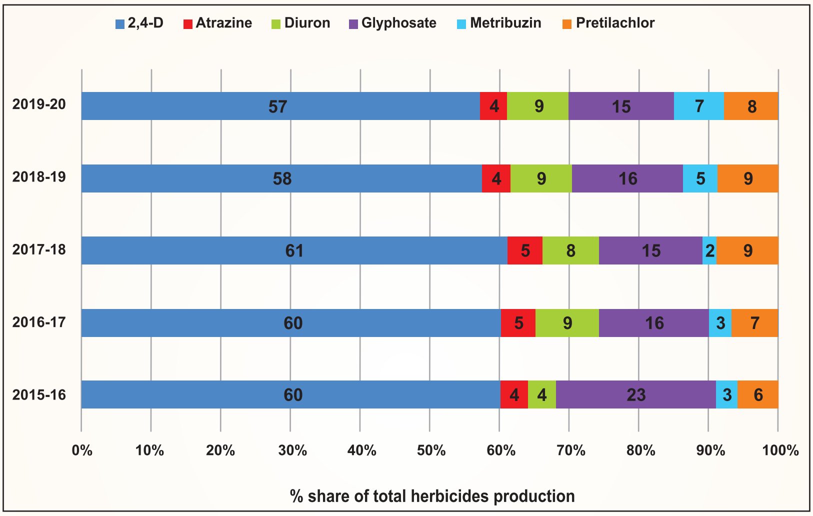

Fig. 7: Per cent share of key herbicides in total herbicides production in India
(Data source: https://ppqs.gov.in/statistics)

5.3. Consumption trends and patterns of various pesticide groups in India

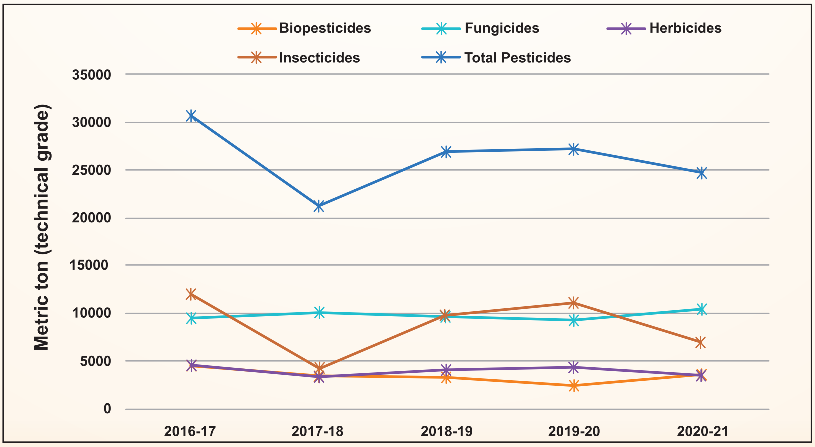

Fig. 8: Consumption trend of different pesticide groups over the years
(Data source: https://ppqs.gov.in/statistics)

Figure 8 clearly depicted that total pesticide consumption has decreased from 30,678 MT to 24, 694 MT during the five years from 2016-17 to 2020-21. Fungicides showed an increasing trend in consumption over the years. The consumption of fungicides in 2016-17 was 9380 MT and it reached to 10425 MT in 2020-21. A significant quantum of decline in consumption (from 11887 MT in 2016-17 to 6987 MT in 2020-21) was found in case of insecticides, among other groups of pesticides. The volume of consumption of herbicides marked a declining trend, it was 4495 MT in 2016-17 and dipped to 3326 MT in 2020-21. Table 6 indicated the estimated compound annual growth rate of consumption of different groups of pesticides in India. Overall, total pesticide consumption showed a negative growth rate over the years (-1.8%). Among different groups of pesticides, only fungicides showed a positive growth rate of 1.3 per cent. Biopesticides consumption depicted the highest negative CAGR (-7.9%) and herbicides recorded growth rate of -3.2 per cent during this period and insecticides registered a growth rate of -1.2 per cent. Figure 9 indicated the percentage share of each pesticide group in total pesticide consumption in the year 2020-21. The highest per cent share (42%) was recorded by fungicide followed by insecticides (28%) and biopesticides (14%). Interestingly, herbicides were at 4th position after biopesticides with 13.5 per cent share in total pesticide consumption.

Table 6. Compound annual growth rate of consumption of different pesticides

S.N.	Pesticides	CAGR (%)
1	Biopesticides	-7.9
2	Fungicides	1.3
3	Herbicides	-3.2
4	Insecticides	-1.2
5	Total Pesticides	-1.8

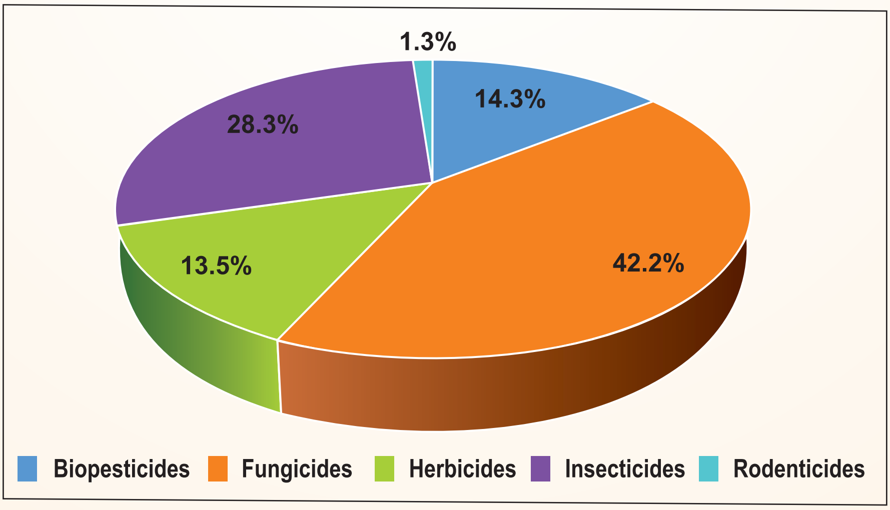

Fig. 9: Per cent share of consumption of different pesticide groups in 2020-21

(Data source: https://ppqs.gov.in/statistics)

5.4. Consumption trends and patterns of herbicides in India

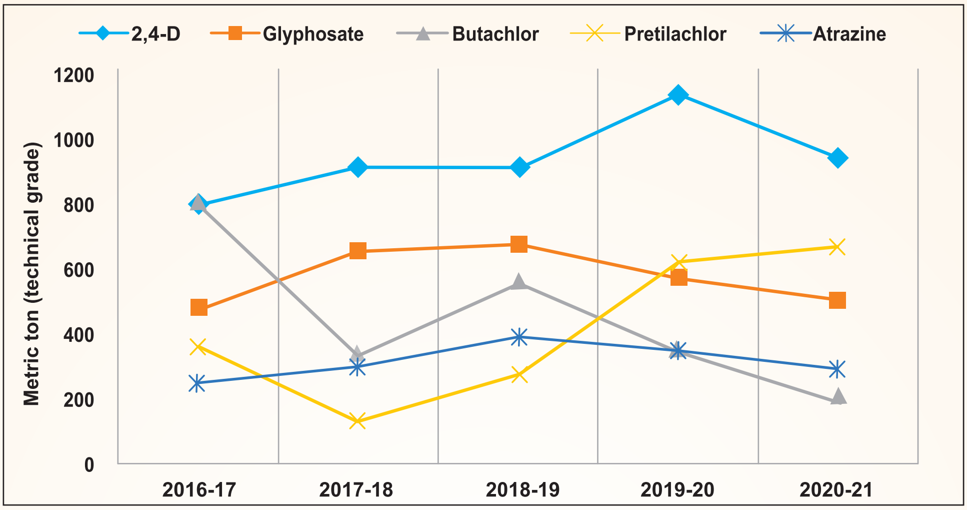

Fig. 10: Consumption trend of top five herbicides in India

(Data source: https://ppqs.gov.in/statistics)

In India, 95 per cent of herbicides used were indigenously produced and the rest 5 per cent were imported from other countries. There were 41 indigenous herbicides and 25 imported herbicides in the data set. For further analysis, the study focused on the top 5 herbicides, which account for a substantial portion (about 70%) of total herbicide consumption in India. Figure 10 showed the trend line chart of consumption of these five key herbicides. Of the 5 herbicides, butachlor was at the highest position in terms of consumption volume (812 MT) in 2016-17 and it was dipped to the lowest position (209 MT) in 2020-21. Whereas, the volume of pretilachlor consumption was 359 MT in 2016-17 and it has increased to 666 MT in 2020-21. Glyphosate showed an increase in consumption volume till 2018-19 (from 478 MT in 2016-17 to 679 MT in 2018-19) and thereafter consistent dip was recorded in the consumption volume. Both 2,4-D and atrazine indicated reasonable levels of increment in the consumption volume over the years and overall total herbicides consumption declined from 4495 MT in 2016-17 to 3325 MT in 2020-21. Table 7 clearly showed that, among the five herbicides, pretilachlor depicted the highest compound annual growth rate (32.1%) followed by 2,4-D (5.8%) and atrazine (4.2%). Both butachlor and glyphosate showed a negative growth rate trend. Figure 11 depicted the per cent share of top 5 herbicides out of the total herbicide consumption in each year. 2,4-D showed the highest per cent share contribution in all the 5 years from 2016-17 to 2020-21. However, butachlor had the same per cent share (18%) as that of 2, 4-D in 2016-17. While considering the recent year (2020-21), 2,4-D occupied the highest per cent share of consumption (28%) followed by pretilachlor (20%) and glyphosate (15%). Further, these five herbicides itself contributed 78 per cent of total herbicide consumption in the year 2020-21.

Table 7. Compound annual growth rate consumption of key herbicides

S.N.	Herbicides	CAGR (%)
1	2,4-D	5.8
2	Glyphosate	-0.3
3	Butachlor	-23.5
4	Pretilachlor	32.1
5	Atrazine	4.2
6	Total herbicides	-3.2

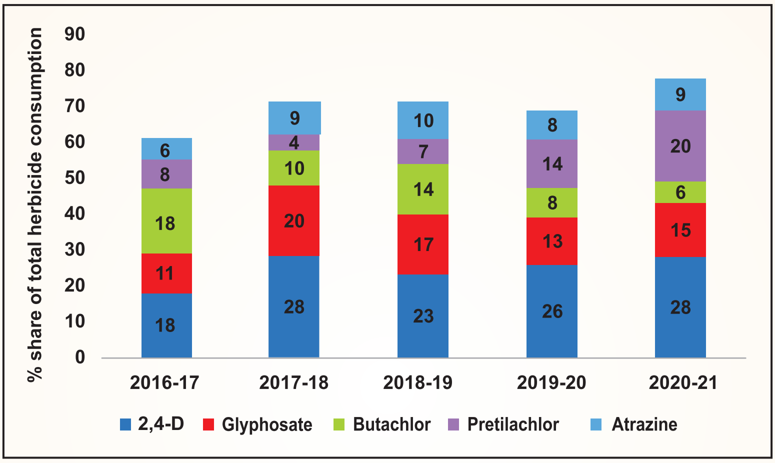

Fig. 11: Per cent share of top five herbicides in total herbicide consumption in India
(Data source: https://ppqs.gov.in/statistics)

5.5. Trends and patterns of demand for various pesticide groups in India

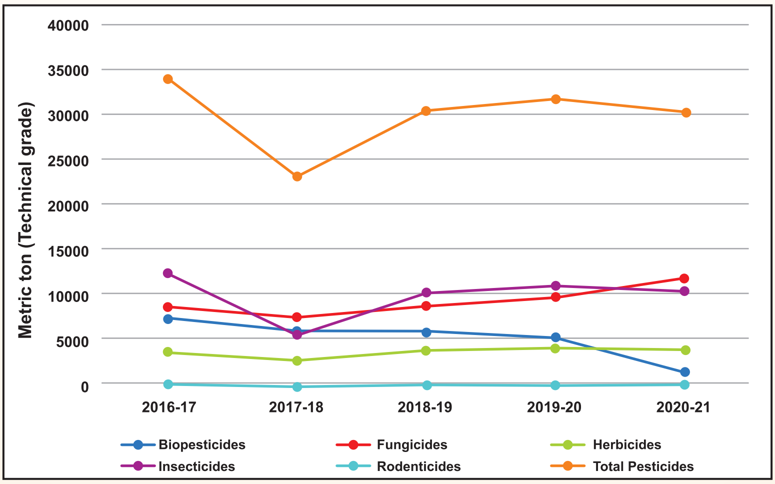

Fig. 12: Demand trend of different pesticide groups over the years
(Data source: https://ppqs.gov.in/statistics)

The demand trend for various groups of pesticides was depicted in Figure 12. It was indicated that total pesticide demand has declined from 34162 MT in 2016-17 to 30426 MT in 2020-21. There was a sharp decline in 2017-18, with demand of 23 440 MT and rest all the years it was more than 30 thousand MT. From the figure, it could be seen that this decline is attributed to the decline in demand for insecticides observed in 2017-18. Fungicides saw the greatest increase in demand, with 9010 MT in 2016-17 rising to 12152 MT in 2020-21. Though there was an uneven trajectory throughout the year, herbicides also witnessed an increase in demand from 4090 MT in 2016-17 to 4316 MT in 2020-21. Whereas, insecticides demand declined from 12678 MT in 2016-17 to 10789 MT in 2020-21. Table 8 showed the compound annual growth rate of different pesticide groups. The perusal of the table indicated that total pesticide demand grew at 0.8 per cent and the highest growth rate was registered by fungicides (8.8%). Biopesticides showed a negative growth rate (-25.7%) and all other pesticides depicted a positive growth rate in this period. Despite a decrease in total demand for insecticides and rodenticides, growth rates remained positive at 3.3 and 3.2 percent, respectively. Percentage share of each pesticide in the total volume of pesticides demanded in 2020-21 was depicted in figure 13. The highest per cent share (40%) was occupied by fungicides followed by insecticides (35%) and herbicides (14%).

Table 8: Compound annual growth rate of demand for pesticides in India

S.N.	Pesticides	CAGR (%)
1	Biopesticides	-25.7
2	Fungicides	8.8
3	Herbicides	4.9
4	Insecticides	3.3
5	Rodenticides	3.2
6	Total Pesticides	0.8

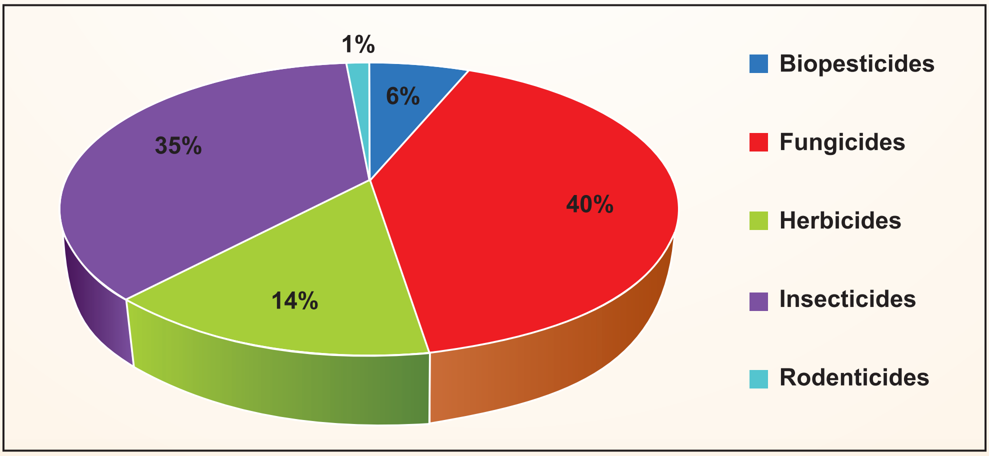

Fig. 13: Per cen share of pesticide groups in total demand for pesticides in 2020-21

(Data source: https://ppqs.gov.in/statistics)

5.6. Trends and patterns of demand for herbicides in India

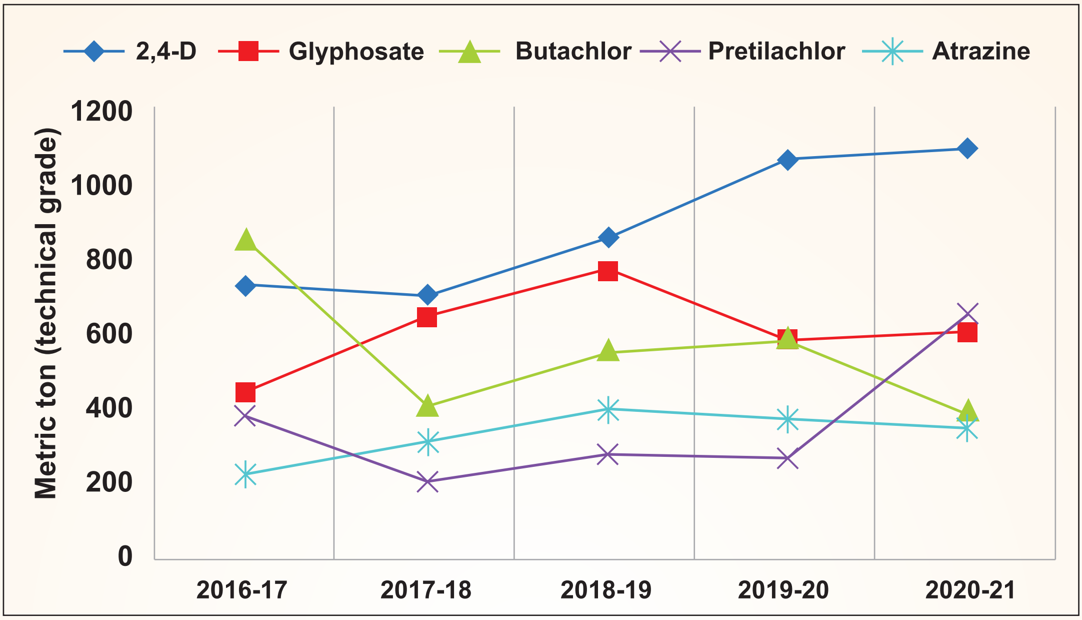

Fig. 14: Demand trend of key herbicides in India
(Data source: https://ppqs.gov.in/statistics)

There were 49 indigenous herbicides and 20 imported herbicides that were demanded in various quantities from 2016-17 to 2020-21. In other words, more than 99 percent of herbicides demanded are indigenous, with only 1% or less imported almost every year. The average volume demanded over the five years was calculated and ranked based on the quantity demanded. The top five herbicides in terms of quantity demanded were then considered for further analysis. Figure 14 depicted the demand trend for these key herbicides, which showed a varying level of demand over time. Except for 2017-18, demand for 2,4-D has consistently increased over the years. The demand for 2,4-D increased from 736 MT in 2016–17 to 1107 MT in 2020–21. Demand for butachlor, on the other hand, fell steadily during this period, from 858 MT in 2016-17 to 392 MT in 2020-21. Although demand for pretilachlor varied from year to year, a significant increase in demand (379 MT to 659 MT) was seen over the five years ending in 2020–21. Glyphosate demand increased steadily until 2018-19, then decreased slightly before increasing again in 2020-21. The compound annual growth rate of demand for key herbicides were given in table 9. The perusal of the table indicated that total herbicides grew at a rate of 4.9%, with pretilachlor showing the highest growth rate (14.7%). 2,4-D and atrazine had the second and third-highest growth rates, with 13.1 and 10.6 percent, respectively. Only butachlor (-11.4%) showed a negative growth rate. Figure 15 shows the percentage share of the top five herbicides in total herbicide demand in India. These five herbicides account for more than 60% of total herbicide demand in the five years ending in 2020-21, and this figure was close to 90% in 2017-18. Except for butachlor, all other herbicides experienced an increase in their percentage share of total herbicide demand every year. In case of butachlor, the share fell from 21 per cent in 2016-17 to 9 per cent in 2020-21. In case of 2,4-D, the share increased from 18 to 26 per cent, while pretilachlor experienced the greatest increase in percentage share (9% to 15%) during this period.

Table 9: Compound annual growth rate of demand for key herbicides in India

S.N.	Herbicides	CAGR (%)
1	2,4-D	13.1
2	Glyphosate	5.0
3	Butachlor	-11.4
4	Pretilachlor	14.7
5	Atrazine	10.6
6	Total herbicides	4.9

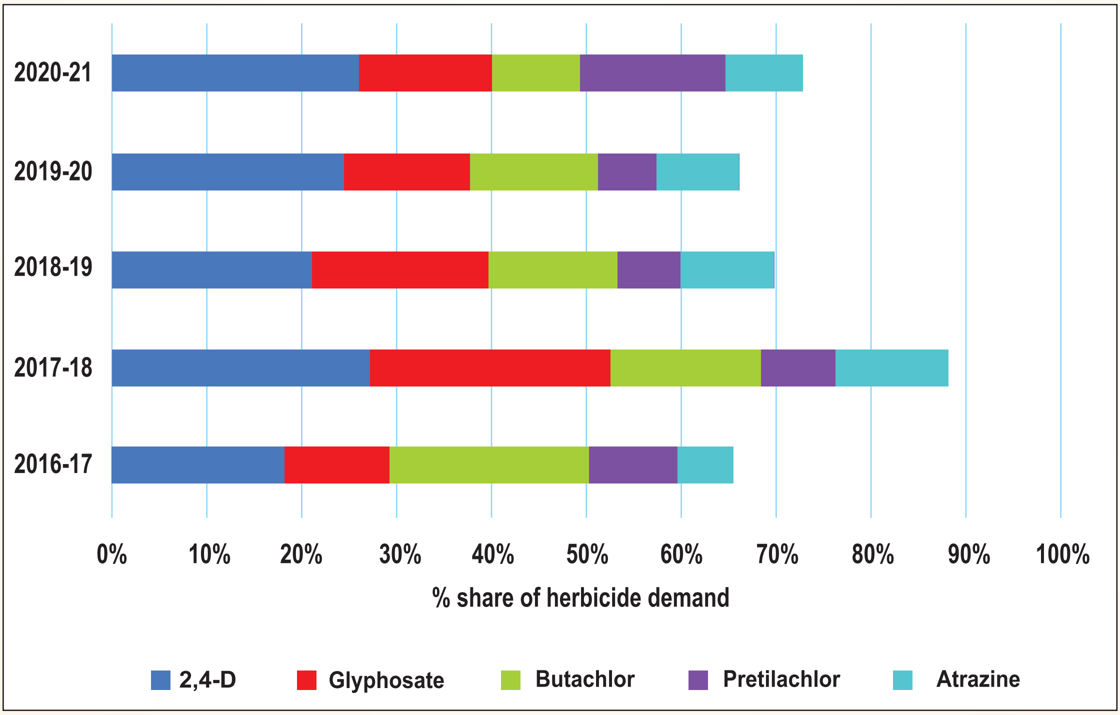

Fig. 15: Per cen share of key herbicides in total herbicide demand in India
(Data source: https://ppqs.gov.in/statistics)

6. Herbicide use and economic benefit: A case study from central India

The herbicide usage in major crops and economic benefit accrued due to herbicide use in central India has been arrived based on the secondary data collected from the the offices of Joint Director, Deputy Director and block level offices of the Department of Agriculture, Government of Madhya Pradesh.

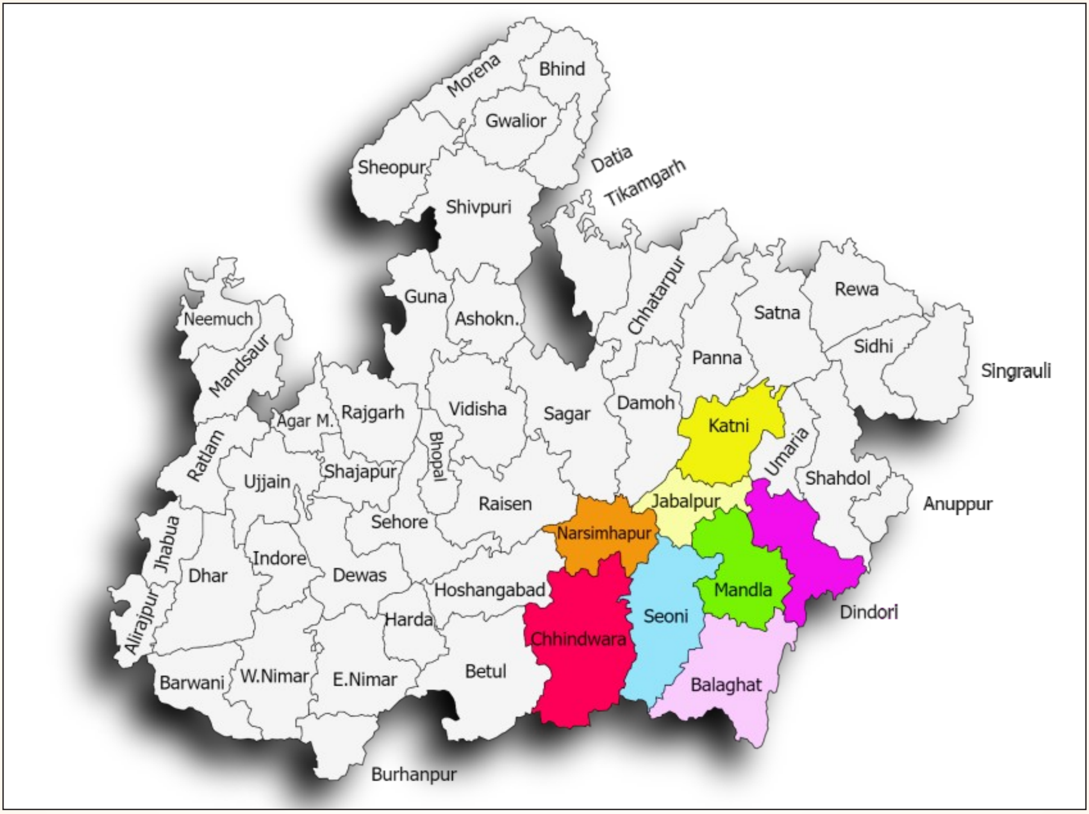

Fig. 16: Madhya Pradesh map highlighted with 8 districts in the Jabalpur agricultural division

Jabalpur agricultural division has been selected for the study and four major crops viz. rice, wheat, maize and greengram were taken into consideration. There are eight districts in the Jabalpur agricultural division viz. Balaghat, Chhindwara, Jabalpur, Katni, Mandla, Dindori, Narsinghpur and Seoni. After obtaining the area under herbicide usage for each crop, the economic benefit accrued was computed based on the On-farm research (OFR) trial data of ICAR-DWR, Jabalpur. ICAR-DWR has been conducting OFR trials in various districts in Madhya Pradesh since many years. Present study considered net returns over farmer's practice that has been derived from the data of 5 district in the Jabalpur division wherein OFR studies were held previously.

Figure 17 depicted total cropped area and area under herbicide use in four major crops that has been grown in Jabalpur agricultural division. Wheat crop covered largest area (11.93 lakh ha) in the division followed by rice (11.46 lakh ha), maize (5.74 lakh ha) and greengram (0.19 lakh ha). In terms of herbicide use coverage, rice crop recorded the largest area (7.68 lakh ha). Of which 67 per cent of total cropped area of rice uses herbicides for weed management. In case of wheat, it is 61 per cent of the total wheat growing area. However, in percentage terms, maize crop recorded with the highest coverage in herbicide use area (73%) followed by greengram (68%). As far as different districts in the division is concerned, the pattern of herbicide use area showed a different trend. As an obvious fact, based on the cropping pattern of the particular district, herbicide use area coverage also differs. For example; in case of Katni district wheat crop occupied the highest cropped area and therefore the highest herbicide coverage as well (69% of total cropped area). Whereas, in Mandla district, it is rice (71% of total cropped area) and it is maize in Chihindwara district (70% of total cropped area). In a nutshell, all four crops indicated more than 50 per cent of cropped area under herbicide use. This pointed the fact that herbicide use is inevitable to manage the weed menace in the crop field and thereby to obtain better returns for farmers.

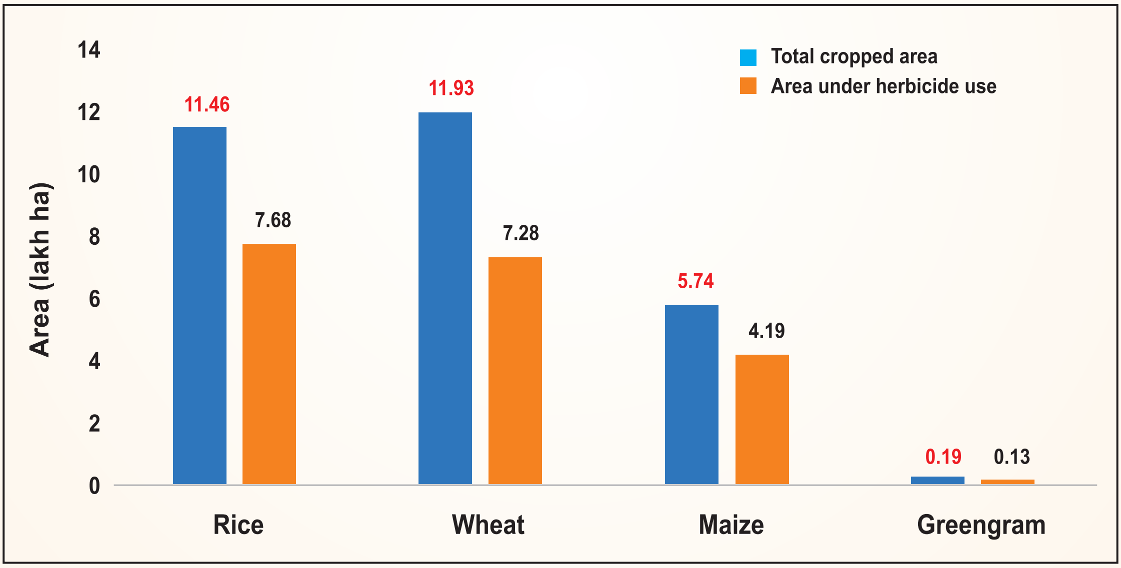

Fig. 17: Extent of area under herbicide use in major crops grown in Jabalpur division

Herbicide use to control weeds in crops bring better returns to farmers. Table 10 indicated the economic benefit accrued due to herbicide use in major crops grown in Jabalpur division. Based on the OFR data of ICAR-DWR, Jabalpur, the average net returns over farmer's practice in each crop were calculated. The highest net returns per ha was recorded in case of greengram (₹ 9,400) followed by maize (₹ 8,400) and rice (₹ 7,600). The price of the crops in a particular year is also dependent on the net returns obtained. Considering this net retunes/ha value, the total returns due to herbicide use were calculated using the data of area coverage under herbicide use in each crop. It was indicated that, rice crop fetched the highest amount (₹ 583.5 crores) followed by wheat (₹ 524 crores) and maize (₹ 352 crores). Though, it is very clear that crops with the largest area coverage under herbicide use fetched better returns, the additional returns that accrued to farmers due to the herbicide used alone make a considerable difference in their net farm income.

Table 10. Economic benefit accrued due to herbicide use in major crops

S.N.	Crop	Net returns over Farmer's practice (₹/ha)*	Total Returns due to herbicide use (₹ crores)
1	Rice	7,600	583.5
2	Wheat	7,200	524.2
3	Maize	8,400	351.8
4	Greengram	9,400	12.1

*Mean value of 5 districts wherein ICAR-DWR, Jabalpur conducted OFR studies

7. Advantages and drawbacks of herbicide use

The usage of herbicides and their advantages and drawbacks have been extensively studied over the past six decades. Herbicide use is increasing day by day since alternative control measures do not provide an effective and cost-cutting substitute for herbicides. Herbicide efficacy and safety are greatly influenced by soil and climate. These vary greatly between countries, as does the legislation that governs their use. Certain advantages and drawbacks of herbicide use are listed hereunder.

Table 11. Advantages and drawbacks of herbicide use

Advantages	Drawbacks
• Herbicides are easy to use and kill weeds in situ without disseminating propagules. • Herbicides are suitable for closely spaced crops where other methods are not viable.	• Some herbicides are non-biodegradable and are harmful for a long period. Heavy dose of herbicides affect microbial population of the soil • The improper use of herbicides may also cause storm water infiltration into groundwater and then the surface waters, such as ponds, streams, rivers, and lakes.

Table contd...

• Herbicides are relatively cheap, and most of the time cheaper than manual weeding. • Herbicides aid crop growth by eliminating weeds that compete for essential resources like water, nutrients, and light, as well as release toxins that interfere with crop growth. • Herbicides are very useful in the monsoon season where continuous rainfall can impede weeding. • Herbicides are convenient to use on thorny or spiny weeds • Control weeds on erodible soil where tillage may accelerate soil and water erosion	• Herbicide use may alters the habitat of birds, mammals, insects, and other animals by altering the vegetation of treated sites. • Arbitrary and indiscriminate usage of herbicides and pesticides may result in endometriosis-like problems in humans • Crop plants may be damaged if herbicides are not used properly, especially if a high dose is used or spraying occurs during a time when the crop species is sensitive to the herbicide. • Build-up of herbicide-resistant biotypes where the same herbicide has been used repeatedly for several years • Improper handling of herbicides may cause certain skin diseases in humans.

8. Herbicide resistance: An inevitable curse

Herbicide resistance is the inherited ability of a plant to survive and reproduce following exposure to a dose of herbicide (field dose) normally lethal to the wild type. In other words, Herbicide resistance can be defined as the acquired ability of a weed population to survive an herbicide application that previously was known to control the population (WSSA, 2011). Detection of the first herbicide-resistant weeds happened in 1957 (Hilton, 1957) which mark the abrupt end of the golden age of herbicides, and in 1968, simazine or atrazine-resistant common groundsels (*Senecio vulgaris* L.) were found to have the first serious case of herbicide resistance (Ryan 1970). There are currently 515 unique cases (species x site of action) of herbicide resistant weeds globally, with 267 species (154 dicots and 113 monocots). Weeds have evolved resistance to 21 of the 31 known herbicide sites of action and to 165 different herbicides. Herbicide resistant weeds have been reported in 97 crops in 72 countries (http://www.weedscience.org, accessed on 08.11.22), and no new site of action has been marketed since 1991 (Duke, 2012). Since 1970, there have been nine new cases of herbicide-resistant weed populations reported annually on average (Heap, 2013), and the rate appears to be increasing despite all the weed scientists' efforts to educate and train farmers on how to handle resistance. It is now widely acknowledged that herbicide resistance is a result of the adaptive evolution of the weed population to the intense selection pressure exerted by herbicides (Jasieniuk *et al*. 1996 and Neve *et al*. 2009). Resistance to herbicides in arable weeds is increasing rapidly worldwide and threatening global food security. Resistance has now been reported to all major herbicide modes of action despite the development of resistance management strategies in the 1990s (Délye *et al*. 2013). The graph (Figure 18) presents the chronological increase in resistance to 5 herbicide sites of action. The letters refer to the Weed Science Society of America code (WSSA) to identify herbicide sites of action. Different herbicide sites of action have different propensities to select resistance. PSII inhibitor (Group 5, 6, 7) herbicides, primarily atrazine resistant weeds in corn, dominated in the USA and Europe in the 1970's and 80's. ALS inhibitor (Group 2) herbicides are the most prone to resistance. Note that the Y axis is the number of species (because a species is only plotted once per site of action).

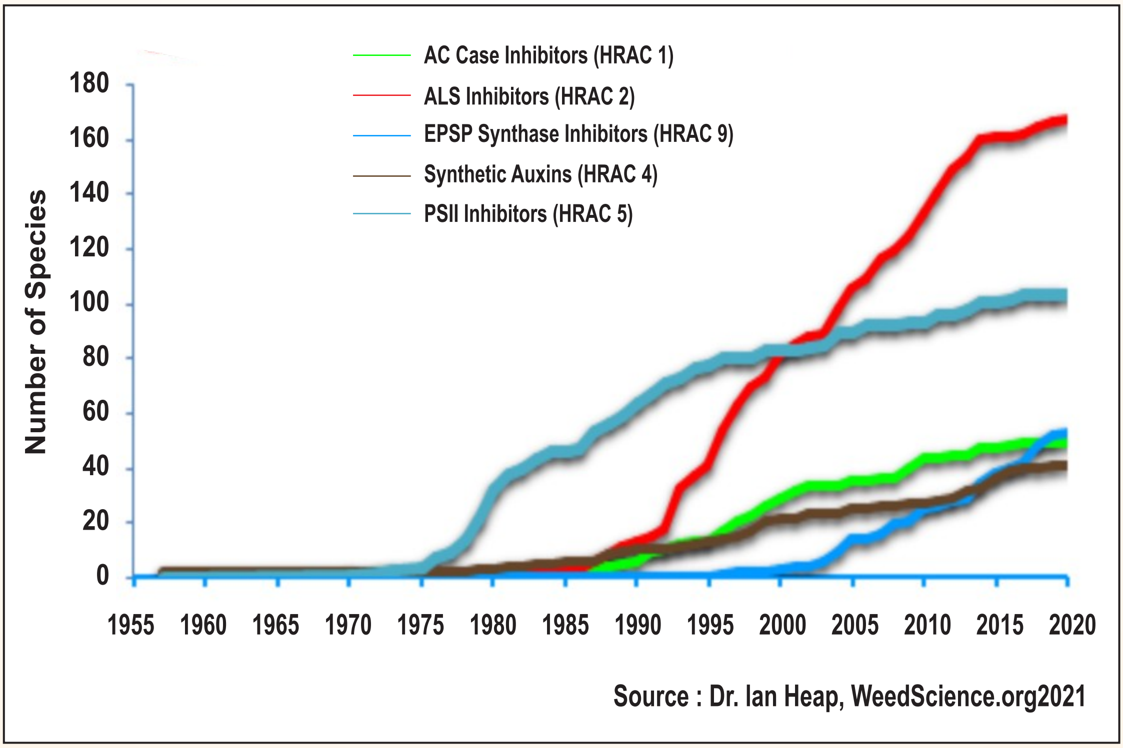

Fig. 18: Number of Resistant Species for Several Herbicide Sites of Action (HRAC Codes)

A bird's eye view of the herbicide resistance statistics in the world segregated in different ways is depicted in Fig 19. Among the top 10 weed families, the Poaceae family had reported with the highest number of herbicide resistant species (86) followed by Asteraceae (44) and Brassicaceae (22). With respect to weed species resistance to multiple herbicide sites of action, Lolium rigidum topped with 14 number of sites of action followed by Echinochloa crus-gullis var. crus-galli and Poa annua with 11 and 10 sites of action respectively. Herbicide actives wise resistance data indicated that highest number of species (66) in case of atrazine followed by glyphosate (51) and tribenuron-methyl (45). 2,4-D was at the bottom position among top 15 with 25 species. In terms of different crop situations, wheat topped with 81 herbicide resistant species followed by maize and rice with 63 and 52 respectively. As far as India is concerned, there are reports of multiple herbicide resistance in different weeds. Little seed canary grass (Phalaris minor Retz.), a troublesome weed of wheat in India, has evolved multiple herbicide resistance (MHR) across three modes of action: photosynthesis at photosystem II site A, acetyl-coA-carboxylase (ACCase) and ALS inhibition (Table 12). The MHR populations had a low level of sulfosulfuron resistance but high level of resistance to clodinafop and fenoxaprop. Some of the resistant populations have GR50 values for clodinafop 12 times higher than susceptible population. The multiple herbicide resistant populations (resistant to sulfosulfuron, clodinafop, pinoxaden and isoproturon) are susceptible to the triazine (metribuzin and terbutryn) and dinitroaniline (pendimethalin and trifluralin) herbicides. Triazine herbicides have selectivity problem in wheat and due to lack of knowledge and non-availability of effective herbicides many farmers are facing severe yield losses due to multiple herbicide resistance(Chhokar and Sharma, 2008; Singh, 2015). In addition, Rumex dentatus and Cyperus difformishad shown resistance for the mode of action:inhibition Acetolactate Synthase.

Table 12. Details of herbicide resistant weeds in India

S.N.	Species	Common Name	Year of reporting	Site of Action
1	*Phalaris minor*	Little seed Canary grass	1991	PSII inhibitors-Serine 264 Binders (C1 C2/5)
2	*Phalaris minor*	Little seed Canary grass	1994	Inhibition of Acetyl CoA Carboxylase (A/1)
3	*Phalaris minor*	Little seed Canary grass	2006	Multiple Resistance: 3 Sites of Action Inhibition of Acetyl CoA Carboxylase (A/1) Inhibition of Acetolactate Synthase (B/2) PSII inhibitors - Serine 264 Binders (C1 C2/5)
4	*Phalaris minor*	Little seed Canary grass	2013	Inhibition of Acetolactate Synthase (B/2)
5	*Rumex dentatus*	Toothed Dock	2014	Inhibition of Acetolactate Synthase (B/2)
6	*Cyperus difformis*	Smallflower Umbrella Sedge	2017	Inhibition of Acetolactate Synthase (B/2)

Source: https://weedscience.org/summary/country.aspx?CountryID=21

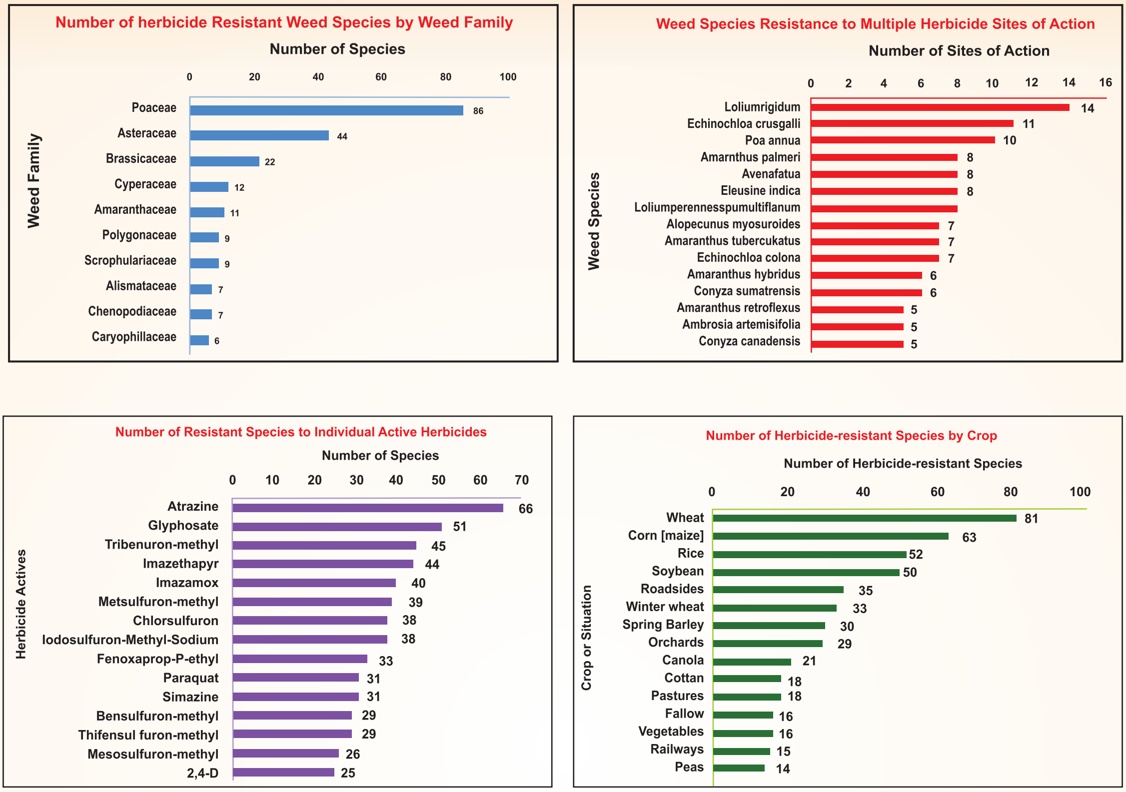

Fig. 19: Global picture of herbicide resistance statistics
(Source: Dr. Ian Heap, WeedScience.org 2021)

9. Conclusion

The use of pesticides in Indian agriculture in general and herbicides in particular is unavoidable. A large portion of farmers in India fell under the small and marginal category and have less than 2 ha of land. In this scenario, they are bounded to use pesticides in order to prevent loss from weeds, insects, diseases, etc., and thereby tap the maximum production potential from their constrained landholdings. The present study indicated that total pesticide production in the country depicted a positive growth rate trend over the years and herbicides topped among other pesticide groups. Metribuzin registered the highest growth rate in production, followed by diuron and pretilachlor. Further, a decline in the growth rate of total pesticide consumption was observed. Among the various pesticide groups, barring fungicides, all other pesticides showed a negative compound annual growth rate. With respect to per cent share of consumption, fungicides recorded the highest share followed by insecticides. Five herbicides viz. 2,4-D, glyphosate, butachlor, pretilachlor and atrazine were identified as the leading herbicides in terms of volume of consumption as well as per cent share of total consumption of herbicides. Pretilachlor showed the highest growth rate during the years considered for the study whereas 2,4-D recorded with highest per cent share of consumption in all the years. In terms of demand, except biopesticides, all other pesticides depicted a positive growth rate trend and fungicides exhibited the highest growth rate, among others. Demand for 2,4-D has consistently increased over the years while butachlor demand, on the other hand, fell steadily during this period. Pretilachlor showed the highest compound annual growth rate in demand followed by 2,4-D and atrazine, respectively. Among five key herbicides, barring butachlor, all other herbicides saw an increase in their percentage share of total herbicide demanded every year. A selective study on herbicide use in central India revealed that more than half of the cropped area in rice, wheat, maize, and greengram was using herbicides to manage the weed menace. Moreover, the additional profits gained from the use of herbicides are substantial in comparison with the conventional farmer's practice. Reduction in cost of cultivation when herbicides were used in place of manual weeding and improved yield due to better control of weeds contributed to fetching higher returns to the farmers. To summarise, as the extent of herbicide use in agriculture increased, farmers realized higher net returns per unit area cropped. Therefore, encouraging the prudent and timely use of herbicides would significantly increase farm income.

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