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# Weed management in maize-based cropping system

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## ABSTRACT

Maize (*Zea mays* L), being a $C_4$ plant, is one of the most vibrant food grain crops under diverse edaphological conditions. In India, maize-wheat is by and large a predominant cropping system that is followed on a large scale, particularly in central and northern part of the country. The low productivity of maize in India, as compared to major maize growing countries of the world, can be attributed to several limiting factors, of which poor weed management poses a major threat to crop productivity. The most important weeds that can be associated with maize/maize-based cropping systems in the country are *Echinochloa colonum*, *Brachiaria ramosa*, *Digitaria sanguinalis*, *Dactyloctenium aegyptium*, *Eleusine indica*, *Setaria glauca*, *Sorghum halepense*, *Panicum* spp. *Cynodon dactylon*, *Digitaria setigera*, *Digitaria ciliaris*, and *Leptochloa chinensis* among grasses; *Ageratum conyzoides*, *Galinsoga parvif]ora*, *CommeIina benghalensis*, *Undernia cilata*, *Polygonum hydropiper*, *Euphorbia geniculata*, *Oxalis latifolia*, *Celosia argentea*, *Cleome viscose*, *Sida acuta*, *Aschynomene indica*, *Acanthospermum hispidum*, *Portulaca oleracea*, *Phyllanthus niruri*, *Amaranthus viridis*, *Acalypha indica*, *Tridax procumbens*, *Ipomoea pestigridis*, *Parthenium hysterophorus* and *Euphorbia hirta* among non-grassy weeds and *Cyperus rotundus* and *Cyperus iria* among sedges. In the rainy season, it was reported thet the emergence of maize and weeds was simultaneous and the first 20-60 days was the most critical period of competition for the crop. However, in winter maize the period beyond 30 days and up to 45 days after sowing was detrimental to maize growth. In India, presence of weeds reduce the maize yields by 27-60%, depending upon the growth and persistence of weed population. The agronomic manipulations, *viz*. tillage and inter-cultivation, intercropping, mulching, cover crops, crop rotation, higher seed rate or plant populations, planting at closer spacing, nutrient management, planting methods, and other agro-techniques are used for weed management in maize/maize-based cropping systems. However, herbicides play a key role providing an option of economical weed management.

**Key words:** Cropping system, Herbicides, Maize, Weed management

Maize (*Zea mays* L) is one of the most versatile cereal crops having wider adaptability under diverse soil and climatic conditions. Globally, maize is known as the queen of cereals because it has the highest genetic yield potential amongst the cereals owing to its better dry matter accumulation efficiency in a unit area and time particularly up to $30^0$ North and South latitude. Maize was first used as a source of food by ancient American and Indian civilizations and it also played an important role in their cultural heritage. These civilizations were responsible for its early domestication and utilization which helped to spread its acreage in various parts of the world. Today, maize has become one of the leading food grain crops in many parts of the world, not only in tropical and subtropical areas but also in temperate and high hill ecologies. It is cultivated in an area of about 150 M ha in 160 countries in diverse soil types, climate, and management practices with wider plant biodiversity that contributes about 36% towards the global food grain production (Anonymous 2013). It is the third most important crop of India after rice and wheat that occupies an area of about 8.67 M ha with an average productivity of about 2.57 t/ha compared to the world average productivity of about 4.94 t/ha (Anonymous 2014). As maize has wide adaptability and compatibility under diverse soil and climatic conditions, hence it is considered as one of the potential drivers of crop diversification under different situations and is cultivated in sequence with different crops under various agro-ecologies of the country. Among different maize-based cropping systems in India (Table1), maize-wheat is a dominant cropping system cultivated in an area of about 1.8 M ha mainly in rainfed ecologies. Maize-wheat is the third most important cropping system after rice-wheat and rice-rice that contributes about 3% in the national food basket (Anonymous 2013). The other

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**Table 1. Maize-based sequential cropping systems in different ago-climatic zones of India**

| Agro-climatic region | Cropping system | |
|---|---|---|
| | Irrigated | Rainfed |
| Western Himalayan region | Maize-wheat, maize-potato-wheat, maize-wheat-greengram, maize-mustard, maize-sugarcane | Maize-mustard maize-legumes |
| Eastern Himalayan region | Summer rice-maize-mustard, maize-maize, maize-maize-legumes | Sesame-rice + maize |
| Lower Gangetic plain region | Autumn rice-maize, jute-rice-maize | Rice-maize |
| Middle Gangetic plain region | Maize-early potato-wheat-mungbean, maize-wheat, maize-wheat-mungbean, maize-wheat-urdbean, maize-sugarcane-mungbean | Maize-wheat |
| Upper Gangetic Plain region | Maize-wheat, maize-wheat-mungbean, maize-potato-wheat, maize-potato-sunflower, maize-potato, onion,maize-potato-sugarcane-ratoon, rice-potato-maize | Maize-wheat maize-barley maize-safflower |
| Trans Gangetic plain region | Maize-wheat, maize-wheat-mungbean, maize-potato-wheat, maize-potato-sunflower, maize-potato-onion, mungbean-maize-toria-wheat, maize-potato-mungbean | Maize-wheat |
| Eastern plateau and hills region | Maize-groundnut-vegetables, maize-wheat-vegetables | Rice-potato-maize jute-maize-cowpea |
| Central plateau and hills region | Maize-wheat | Maize-groundnut |
| Western plateau and hills region | Sugarcane + maize | |
| Southern plateau and hills region | Rice-maize Maize-rice | Sorghum-maize, maize-sorghum-pulses, maize-potato-groundnut |
| East coast plain and hills region | Rice-maize-pearlmillet, maize-rice, rice-maize, rice-rice-maize | Maize-maize-pearlmillet rice-maize + cowpea |
| West coast plain and hills region | Maize-pulses, rice-maize | Rice-maize, groundnut-maize |
| Gujarat plains and hills region | Maize-wheat | Rice-maize |
| Western dry region | maize-mustard, maize-chickpea | Maize + legumes |
| Island region | Rice-maize | Maize-rice, rice-maize + cowpea, rice-maize-urdbean, rice-rice-maize |

Source: Yadav and Prasad (1998)

major maize-based systems in India are maize-mustard, maize-chickpea, maize-maize, cotton-maize etc. Recently, due to the changing scenario of the natural resource base, rice-maize has emerged as potential maize-based cropping system in peninsular and eastern India besides the winter maize cultivation in traditional north-west and central Indian cropping systems.

As mentioned elsewhere the low productivity of maize in India as compared to world productivity can be attributed to several limiting factors and all but the most important amongst these has been the poor weed management which poses a major threat to crop productivity. Weeds, being hardier in nature compete with maize plants for nutrients, water, sunlight and space during entire vegetative and early reproductive stages of maize, they transpire a lot of valuable conserved moisture and absorbs large quantities of nutrients from the soil and their relative density plays a significant role in reducing the yield of crop. Also, wider spacing and slow initial growth of maize favours the growth of weeds even before crop emergence. The presence of weeds reduces the photosynthetic efficiency, dry matter production and distribution to economical parts and thereby reduces sink capacity of crop resulting in poor grain yield. In

**Table 2. Maize-based intercropping systems in India**

| Intercropping system | Suitable area/situation |
|---|---|
| Maize + pigeonpea | All maize growing areas |
| Maize + cowpea | |
| Maize + mungbean | |
| Maize + urdbean | |
| Maize + sugarcane | |
| Rice + maize | |
| Maize + soybean | |
| Maize + high value vegetables | Peri-urban interface |
| Maize + flowers | |
| Baby corn + vegetables | |
| Sweet corn + vegetables | |

Source: Yadav and Prasad (1998)

agro ecosystems, ideal environmental conditions provided for optimal crop productivity are being exploited by the associated weeds. In India, the presence of weeds, in general reduces the maize yield by 27-60%, depending upon the growth and persistence of weed population in maize crop (Tripathi *et al*. 2005, Sharma and Gautam 2006, Sunitha *et al.* 2010, Jat *et al.* 2012, Singh *et al.* 2015, Kumar *et al.* 2012). Thus, proper weed management strategies would continue to play a key role to meet the food, feed and fiber demands of an increasing population of India. Hence, it is required to redesign the strategies from time to time for the successful management of weeds. Therefore, it is essential to review the progress so far made on maize based cropping systems vis-à-vis weed management strategies in India to redesign the future methodologies for the successful management of ever increasing problems of weeds.

**Weed spectrum in maize-based cropping systems**

*Cyperus rotundus* and *Trianthema portulacastrum* were the dominant weed species in spring maize at Hissar (Singh *et al.* 1998). Whereas in Orissa, *Cynodon dactylon, Digitaria setigera, Digitaria ciliaris, Leptochloa chinensis, Daetyloctenium aegyptium, E1eusine indica, Cyperus rotundus, Cyperus iria, Celosia* argentea, *Commelina benghalensis, Sida acuta, Aschynomene indica* and *Acanthospermum hispidum* were found dominant weeds in rainfed maize (Rout and Stapathy 1996). *Commelina benghalensls, Cyperus rotundus, Cynodon dactylon, Portulaca oleracea, Phyllanthus niruri, Amaranthus viridis, Acalypha indica* and *Tridax procumbens* were the prevalent weed species in maize at Dharwad (Lamani *et al.* 2000). On the other hand, Sharma and Thakur (1998) reported that *Digitaria sanguinalis, E1eusine indica, Setaria glauca, Panicum* spp., *Cynodon dactylon, Sorghum halepense* among grasses, *Cyperus* spp. among sedges and *Commelina benghalensis, Galinsoga parviflora, Ipomoea pestigridis* and *Euphorbia hirta* among broad-leaved weeds were dominant in maize under mid hill conditions of North-Western Himalayan regions. Whereas, Jat *et al.* (2012) reported *Cyperus rotundus, Digera arvensis, Commelina bengalensis, Euphorbia hirta, Parthenium hysterophorus* and *Cleome viscosa* in maize crop of maize-wheat cropping system in Bihar. Similarly, Singh *et al*. (2015) observed *Celosia argentea, Commelina benghalensis, Dactyloctenium aegyptium, Digera arvensis, Eluesine indica, Echinochloa colona, Corchorus trilocularis, Leptochloa chinensis* and *Rumax acetosella* as dominant weed flora in maize in maize-wheat cropping system at IARI, New Delhi. *Commelina benghalensis, Ageratum conyzoides, Echinochloa colona, Panicum dichotomiflorum, Cyperus iria, Digitaria sanguinalis, Polygonum alatum* and *Aeschynomene indica* were dominant weeds observed under Palampur conditions of Himachal Pradesh (Kumar *et al.* 2012). While Sunitha *et al*. (2010) from Thrupati reported that *Panicum repens, Digitaria sanguinalis, Celosia argentea, Acanthospermum hispidum, Cleome viscosa* were dominant weeds in sweet corn. Whereas at Pantnagar, *Cynodon dactylon, Cyperus rotundus, Echinochloa crusgalli, Echinochloa colona, Agropyron repens, Parthenium hysterophorus, Digitaria sanguinalis, Eclipta alba, Euphorbia hirta, Commelina benghalensis* weeds were observed in maize (Sharma and Gautam, 2006). The differences in weed flora with respect to soil type were also noticed by many workers. In loamy clay soils, *Echinochloa colona, Brachiaria ramosa, Digitaria sanguinalis, Dactyloctenium aegyptium, Eleusine indica, Setaria glauca, Sorghum halepense* and *Panicum* spp. among grasses, *Ageratum conyzoides, Galinsoga parviflora, Commelina benghalensis, Undernia cilata, Polygonum hydropiper, Euphorbia geniculata* and *Oxalis latifolia* among non-grassy weeds and *Cyperus rotundus* among sedges were the major weed flora observed in maize fields at Pantnagar, Uttaranchal (Pandey *et al.* 2001). During *Kharif* season, *Echinochloa colona, Trianthema portulacastrum, Cyperus rotundus* and *Eleusine indica* were the dominant weeds in maize fields at Pantnagar conditions of Uttaranchal. On the other hand during winter season maize *Chenopodium album, Chenopodium murale, AnagalIis arvensis, Melilotus indica, Euphorbia hirta, Convolvulus arvensis* among broad leaved weeds, *Cyperus rotundus* among sedges and *Cynodon dactylon* among grasses were the dominant weed flora in maize at Banswara, Rajasthan (Porwal 2000). During rainy season, *Cyperus rotundus, Cynodon dactylon, Digitaria sanguinalis, Dactyloctenium aegyptium, Parthenium hysterophorus, Commelina benghalensis, Amaranthus viridis, Digera muricata, Euphorbia geniculata* and *Trichodesma indicum* were more prevalent weed flora in maize fields at Hyderabad (Sreenivas and Satyanarayana 1994). On the contrary, *Panicum repens, Dactyloctenium aegyptium* and *Cynodon dactylon, Cyperus rotundus, Trianthema portulacastrum, Parthenium hysterophorus, Flavaria australasica* and *Amaranthus viridis* were dominant weed flora in *Rabi* maize at Coimbatore (Kandasamy and Chandrasekhar 1998). In maize + soybean intercropping system, *Echinochloa colonum, Commelina benghalensis, Physallis minima, Celosia argentea, Setaria glauca, Cyperus rotundus, Ageratum conyzoides* were found dominant (Prasad and Rafey 1995). Similarly, Kumar and Singh (1992) also observed *Cyperus rotundus, Echinochloa colonum, Brachiaria ramosa* and *Commelina benghalensis, Cynodon dactylon, Sorghum halepense* as the dominant weed flora in maize + legume intercropping system. But in· maize-mustard cropping system, primarily a dicot weed *i.e. Trianthema portulacastrum* dominated the monocot weeds in first year, while in the second year monocot weeds dominated the dicot weeds during rainy season (Saikia and Pandey 2001a).

**Critical period of crop-weed competition**

Maize, being a widely spaced crop with slow early growth, allows the weeds to compete easily as compared to other cereal crops. Porwal (2000) observed that in the rainy season, emergence of maize and weeds were simultaneous and found that the first 20-30 days was the most critical period of competition for maize crop. Whereas, Nayital *et al.* (1989) reported that in maize during the rainy season, critical stage of crop weed competition was between 20-60 days after sowing. However, in irrigated winter maize beyond 30 days and up to 45 days after sowing was detrimental to maize growth and caused yield loss in command area of southern Rajasthan (Porwal 1998).

**Agronomic manipulations for weed management**

Herbicide is a key component in almost all weed management strategies, but the indiscriminate use of herbicides has resulted in serious ecological and environmental problems. Thus, a dire need was felt to discover the agronomic manipulations for weed management which are environmentally safe. Further, since environmental protection is a global concern, the age-old agronomic manipulations, *viz.* tillage and inter-cultivation, intercropping, mulching, cover crops, crop rotation, higher seed rate or plant populations, planting at closer spacing, nutrient management, planting methods, and other agro-techniques are used for weed management. The investigations on the agronomic manipulations for weed management in maize and maize-based cropping systems are reviewed below.

**Tillage, inter-cultivation and sowing method:** Tillage, inter-cultivation and sowing method greatly influence weed dynamics in maize. Tillage operations in maize resulted in significant reduction in weed density and weed dry weight at all the stages of crop growth over no-tillage, which resulted in a significantly higher number of cobs per hectare, grain yield and net returns as compared to no-tilled treatment. This might have happened probably due to the fact that favourable soil conditions resulted in better crop growth and development as well as lesser crop-weed competition (Sharma and Gautam 2006). The intercultural operations like mechanical weeding or two hand weedings at 20-30 and 35-45 days after sowing effectively minimized the weed population and increased maize yield (Kandasamy and Chandrasekhar 1998, Saikia and Pandey 2001b, Tripathi *et al.* 2005, Ramachandran *et al.* 2012, Saini *et al.* 2013). To substitute manual weeding, more efficiently, less energy intensive manual and machine-operated tools/ implements have been introduced for weed control in crops (Tajuddin *et al.,* 1991). Sharma *et al.* (2000) reported that hoeing at 15 DAS effectively controlled the weed population at 30 DAS which was less than half (23-32 weeds/m$^2$) as compared with no intercultural operation (67-70 weeds/m$^2$). Further, they put forth that earthing up at 30 DAS effectively controlled diverse weed flora throughout the crop growth period of rainfed maize. Pandey *et al.* (2000) reported that pine needle mulch and earthing up after removing the mulch was most effective to control major weeds in maize. Field preparation with two ploughings followed by two harrowings in baby corn-groundnut cropping sequence resulted in lower weed density and dry weight of weeds and higher economic yields of baby corn and groundnut as compared to one ploughing followed by one harrowing and unploughed Bangalore conditions (Thimmegowda *et al.* 2007). Chopra and Angiras (2008) reported that raised seed bed recorded significantly lowest weed density and dry matter of weeds at 60 days after sowing and at harvest followed by conventional tillage over zero tillage in maize crop.

Raised seed bed and conventional tillage increased grain yield by 13.74 and 16.90% over zero tillage. Likewise, Lal *et al.* (1988) also proved superiority of conventional tillage and ridge tillage over zero tillage in maize. However, Shekar *et al.* (2014) revealed that adoption of continuous zero tillage in wheat-maize cropping system proved statistically at par with zero tillage-conventional tillage in wheat-maize cropping and both of these practices enhanced sedges population significantly over continuous conventional tillage, conventional tillage-zero tillage and furrow irrigated raised bed in wheat-maize system. The stale seed bed in zero tillage and permanent beds with tank mixture of glyphosate + 2,4-D effectively controlled the mixed weed flora in maize (Jat *et al.* 2012). Sowing of maize in maize-wheat cropping system with manual seed drill recorded significantly lower count of *Ageratuim conyzoides,* which was found to be at par with multi-crop planter as compared to zero tillage sowing and conventional seeding at Palampur conditions (Ramesh *et al.* 2014).

**Soil solarization:** Soil solarization by covering of 0.05 mm thick transparent polyethylene during April-May after irrigation was found effective in suppressing weeds and increasing the yield of baby corn as compared to non-soil solarization. One hand weeding at 30 days after sowing in soil solarized treatment was effective in suppressing the weed dynamics and enhanced the productivity of succeeding groundnut crop (Thimmegowda *et al.* 2007). Further they revealed that land preparation and irrigation upto field capacity are essential before solarization which will enhance the solarization effect with respect to controlling of weeds that increased yield of baby corn followed by groundnut.

**Planting pattern and plant population:** A planting pattern of 60 x 20 cm with 83,333 plants/ha recorded significantly lowest density of grasses, sedges and broad-leaved weeds and highest weed control efficiency which was statistically at par with a planting pattern of 75 x 16 cm. These two planting patterns were found to be significantly superior to 60 x 25 and 75 x 20 cm with 66,666 plants/ha. However, planting pattern of 60 x 25 cm recorded highest cob length and green cob weight of sweet corn and planting pattern of 60 x 20 cm recorded significantly higher green fodder yield which resulted in higher net returns (Sunitha *et al.* 2010).

Weed density and biomass was significantly lower with sweet corn (*Zea mays* L. *saccharata*) population of 1,11,111 plants/ha as compared to 83,333 plants/ha and 74,074 plants/ha. The higher and medium crop population of 1,11,111 plants/ha and 83,333 plants/ha increased the cob yield by 10.7 and 6.8%, respectively, while green fodder yield by 13.6 and 10.6%, respectively as compared to the crop population of 74,074 plants/ha (Arvadiya *et al.* 2012). Similarly, Sharma and Gautam (2006) reported that seed rate of 24 kg/ha recorded significantly lower weed density, dry weight of weeds, higher number of cobs per unit area and higher grain yield in maize as compared to 16 and 20 kg seed/ha. The significant reduction in weed density and weed dry weight at higher seed rate might have happened owing to the fact that maximum competitive efficiency of crop was obtained at higher seed rate (Kumar and Walia 2003).

**Nutrient management:** Deshmukh *et al.* (2008) revealed that 100% recommended doses of fertilizers recorded higher weed control efficiency at 30 days after sowing which was at par with 75% recommended doses of fertilizers + 25% nitrogen through FYM as compared to 50% recommended doses of fertilizers + 50% nitrogen through FYM. Similarly, Dubey (2008) reported that application of 100 kg N/ha recorded lower density of *Echinochloa colona*, and *Commelina communis* as compared to 50 kg N/ha in the maize-cowpea intercropping system.

**Application of organic manures:** Organic manuring could exercise either negative or positive influence on weed seed bank and weed competition. Some might enrich soil weed seed reserves through carryover of weed seeds endowed with them by virtue of endozoochory. Some others could deplete the soil seed bank owing to allelopathic principles and their metabolites. Accordingly, a possible component of integrated weed management in a small farm could be the right choice or organic manuring. The application of different organic manures, *viz.* farm yard manure 12.5 t/ha, goat manure 12.5 t/ ha, neem cake 6 t/ha, pungam green leaf manure 6 t/ha and glyricidia green leaf manure 6 t/ha influenced the weed seed bank in the soil as well as the weed growth and crop yield of maize (Jebarathnam and Kathiresan 2006). These manures were applied and incorporated at the time of last ploughing and left undisturbed for 15 days prior to sowing of crop.

Application of farmyard manure increased the seed bank of *Cyperus rotundus* by 23.1%, *Echinochloa* sp. by 14.2% and *Trianthema portulac-astrum* by 28% as compared to control. This might have happened due to the fact that these was on enrichment of soil weed seed bank by the voiding of farm cattle passing on the seeds after feeding on the weed in a viable state due to the process of endozoochory. Whereas all the organic manures of plant origin, *viz.* glyricidia and pungam green leaf manures, pressmud and neem cake reduced the weed density and weed dry matter in maize leading to better crop yields. Reduction in weed seed germination due to these manures was of the highest magnitude of 32.5, 27.4 and + 57.1% in the case of *Cyperus rotundus*, *Echinochloa colona* and *Phyllantus niruri*, respectively. The reduction in weed seed germination and weed seed bank could be attributed to the acidic and allelopathic nature of metabolites released during the decomposition of organic manures of plant origin. Farm yard manure increased the weed density and weed dry matter significantly over the unweeded control (Saraswat *et al.* 2003).

**Intercropping with cover crops/ smother crops:** Saini *et al.* (2013) from Palampur revealed that soybean intercropping + one mechanical weeding (20 DAS) recorded significantly lowest weed dry weight, higher yield attributes and maize equivalent yield which was at par with 2 mechanical weedings (20 and 40 DAS) + mash intercropping in maize among all other treatments (mechanical weeding at 20 DAS, mechanical weedings at 20 DAS and 40 DAS, hand weeding at 20 DAS, hand weedings at 20 DAS and 40 DAS, soybean intercropping, soybean intercropping + hand weeding at 20 DAS and unweeded check). One mechanical weeding at 20 DAS recorded highest benefit-cost ratio of 4.3 followed by 2 mechanical weeding at 20 and 40 DAS and soybean intercropping + one mechanical weeding (20 DAS). Similarly, Deshmukh *et al.* (2008) found that the intercropping of maize + soybean (1:1) + pre-emergence application of pendimethalin 0.75 kg/ha, recorded significantly superior WCE over rest of the treatments. However, Kumar and Thakur (2005) reported that maize intercropped with soybean and blackgram had no significant variations on weed density and weed dry matter accumulation but caused 18.4 and 13.2% reduction in weed density. While Singh *et al.* (2005) from Udaipur, Rajasthan concluded that maize + soybean (1:1 or 1:2) was found effective for controlling weeds in maize.

Blackgram intercropped with maize as smother crop suppressed the weed growth to the extent of 28.3% (Tripathi *et al.* 2005). Maize + soybean (1:1) suppressed the weed species by canopy cover which resulted in highest weed smothering efficiency as compared to maize + greengram (Shah *et al.* 2011). Maize + blackgram (1:1) was effective in controlling weeds and resulted in higher grain yield as compared to maize + blackgram (2:1) and maize + blackgram (2:2) at Raipur, Chhattisgarh (Sanjay *et al.* 2012). Mishra (2014) reported that the maize + potato (1:1), maize + mustard (1:1), maize + toria (1:2), maize + pea (1:2), maize + linseed (1:2) and maize + wheat (1:2) significantly reduced the weed count in winter maize over sole maize. Amongst intercropping treatments, maize + potato (1:1) recorded highest weed control efficiency followed by maize + pea (1:2) at Kanpur, Uttar Pradesh. Hugar and Palled (2008) found that vegetable crops (cowpea, frenchbean, coriander) intercropped with maize reduced the weed density and dry weight accumulation by weeds which resulted in higher maize equivalent yield at Dharwad, Karnataka. Also, maize + cowpea recorded higher weed control efficiency followed by maize + blackgram (Selvakumar and Sundari 2006).

**Brown manuring:** Weeds are controlled by various ways in maize. However, in the current scenario of agriculture, evolving ecofreindly approach of weed control is more advisable to protect the natural resources such as soil flora and fauna including human beings and animals in a holistic manner. In this context, an advanced weed management strategy which has emerged in India is brown manuring. It aims at suppressing the weeds without affecting the soil physico-chemical properties and its associated microbes. It can be achieved through raising green manure crops such as *Sesbania* (dhaincha), sunhemp *etc*. as inter crop and killing the same by application of post-emergence herbicides. *Sesbania* and maize were grown together for 35 days and thereafter, *Sesbania* was knocked down with the application of 2,4-D at 0.5 kg/ha. The killed manure is allowed to remain in the field along with main crop without incorporation/ *in-situ* ploughing until its residue decomposes itself in the soil aiming to add organic manure beside weed suppression by its shade effect. Given the post-emergence spray on green manure leaves resulting in loss of chlorophyll in leaves showing brown in colour is referred to as brown manuring (Tanwar *et al.* 2010).

Brown manuring also helps in suppressing the weeds up to 50% of total weed population on the account of the shade effect of killed green manure till 45 DAS up to which the critical period of crop weed competition continues in maize. Ramachandran *et al.* (2012) revealed that pre-emergence application of alachlor 1.0 kg/ha + brown manuring reduced the density of grasses, sedges, broad-leaf weeds and total weeds, which resulted in higher weed control efficiency of 89.65% among all other herbicidal treatments. This might have happened probably due to an effective control of weeds during the early stage and suppressed the weed growth by the shade effect of *Sesbania* crop residue and rapidly growing canopy of maize at later stages up to harvest.

**Herbicidal methods of weed management**

The critical period of crop weed competition is 3 to 6 weeks after sowing in the case of maize. Clean and weed free cultivation is one of the principles of modern day farming of maize crop. Hence, managing weeds during this period is most critical for higher yields. The manual eradication of weeds has proved its superiority over all the measures in managing weeds. However, the adoption of this technique has not gained popularity amongst the farmers as it is time consuming, labour intensive, expensive and many a times becomes impractical because of scarcity of labour during peak season. Timely weeding is most important to minimize the yield losses and therefore, under such circumstances the only effective tool is left to control the weeds through the use of chemicals. Management of weeds through the use of chemicals has also been found as effective as realized under manual eradication in various crops, including maize with over and above benefits in saving extra costs involved in the use of labour on manual eradication of weeds. Herbicides are one of the crucial factors in a worldwide increase in cereal production. Herbicides contribute effectively and profitably to weed control, environmental protection, and at the same time, saving labour necessary for weed control practices, reduced soil erosion, save energy, increased maize production and reduced the cost of cereal farming. Therefore, herbicides benefit society as a whole. The importance of herbicides in modern weed management in maize production is underscored by the estimates that losses in the agricultural sector would increase to about 500% without the use of herbicides (Bridges 1992, 1994). Nowadays, maize production is facing a difficult situation. The world population is rapidly increasing (over 6 billion inhabitants on Earth's surface now and estimated 9 billion in 2050) (Berca 2004), every day decreasing the arable surface (nearly 2 billion hectares worldwide have been degraded since mid of the previous century) (Scherr and Yadav 1996). However, there is delusion, controversy and lack of knowledge in the world about herbicide use and its potential benefits for the world food production. Clearly the farmer using herbicides in maize production is saving money or effort on mechanical weed control. There is an environmental benefit too in reduced use of fossil fuels and reduced soil disturbance in no-till systems – representing a common benefit to us all. Beneficiaries may be individual farmers, farming communities, business houses, regulatory authorities, researchers, national populations or the whole living world.

There are different categories of herbicides used in maize/maize-based cropping systems to manage weeds based on the time of application of herbicides, *viz.* pre-emergence herbicides, early post-emergence and post-emergence herbicides. Usage of pre-emergence herbicides assumes greater importance in the view of their effectiveness from initial stages. Atrazine, pendimethalin, alachlor, and oxadiargyl are some of the mostly used pre-emergence herbicides applied in maize/maize-based systems.

For controlling the weeds in maize crop, pre-emergence applications or early post-emergence application of atrazine ranging from 0.25 kg/ha to 1.5 kg/ha with weed control efficiency (WCE) of 36-76% depending upon the soil type, pH and seasons has been tested and recommended by different researchers from different locations (Table 3). Likewise, pendimethalin application ranged from 0.5 to 1.5 kg/ha with the weed control efficiency of 52-86% (WCE) has been recommended by different workers depending upon the soil type (Table 4).

However, the infestation of some hardy weeds like *Acrachne racemosa*, *Bracchiaria reptans* and *Commelina benghalensis* etc. is increasing day by day in the maize growing belt, especially where the

**Table 3. Use of atrazine in maize- based cropping systems in different agro-ecologies**

| Dose | Soil parameters | | WCE (%) | Location | References |
|---|---|---|---|---|---|
| | Soil | pH | | | |
| Atrazine 1.5 kg/ha | Clay loam | 5.6 | 60.5 | Palampur (mid hills), (HP) | Kumar *et al.* (2012) |
| | Silty clay loam | 5.6 | 67.8 | CSKHPKV, Palampur | Chopra and Angrias (2008) |
| Atrazine 1.0 kg/ha | Sandy loam | 7.8 | 86.3 | Middle Gujarat | Patel *et al.*( 2006) |
| | Loamy sand | - | 73.4 | Ludhiana | Walia *et al.* (2007) |
| | Clay | 7.4 | 83.5 | Navsari (Gujarat) | Arvadiya *et al.*( 2012) |
| | Sandy loam | 7.6 | 52.6 | New Delhi | Singh *et al*. (2015) |
| | Sandy loam | 7.6 | 52.6 | New Delhi | Singh *et al*. (2015) |
| Atrazine 0.25 kg/ha (*Rabi*) | Sandy loam | 8.0 | 60.9 | Kanpur | Verma *et al.* (2009), Singh *et al.* (2003) |
| Atrazine 0.50 kg/ha (*Rabi*) | Sandy loam | 8.0 | 73.5 | Kanpur | Verma *et al.* (2009), Singh *et al.* (2003) |
| Atrazine 0.5 kg/ha + 2,4-D (sodium salt) 0.5 kg/ha at 30 DAS (*Rabi*) | Clay | - | 53.2 | Junagarh (Gujarat) | Dobariya *et al.* (2014) |
| Atrazine + pendimethalin 0.50 + 0.25 1.0 kg/ha | Clay | 7.4 | 86.3 | Navsari (Gujarat) | Arvadiya *et al*,( 2012) |
| Atrazine *fb* atrazine 1.50 *fb* 0.75 kg/ha | Clay loam | 5.6 | 80.3 | Palampur (mid hills), (HP) | Kumar *et al.* (2012) |
| Atrazine + pendimethalin 0.75 + 0.75 kg/ha | Loamy sand | - | 76.9 | Ludhiana | Walia *et al.(*2007) |
| Atrazine + alachlor 0.75 + 1.25 kg/ha | Loamy sand | - | 78.1 | Ludhiana | Walia *et al.* (2007) |
| Atrazine + pendimethalin *fb* metasulfuron-methyl 0.75+ 0.75 *fb* 0.004 kg/ha | Clay loam | 5.6 | 69.7 | Palampur (mid hills), (HP) | Kumar *et al.* (2012) |
| Atrazine + pendimethalin *fb* 2,4 D 1.0+ 0.50 *fb* 0.75 kg/ha | Clay loam | 5.6 | 67.0 | Palampur (mid hills), (HP) | Kumar *et al.* (2012) |
| Atrazine + alachlor 0.5 + 0.5 kg/ha | Sandy loam | 7.8 | 94.9 | Middle Gujarat | Patel *et al.* (2006b) |
| Atrazine + pendimethalin 0.5 + 0.25 kg/ha | Sandy loam | 7.8 | 97.9 | Middle Gujarat | Patel *et al.* (2006b) |
| Atrazine + metolachlor 0.5 + 0.5 kg/ha | Sandy loam | 7.8 | 94.9 | Middle Gujarat | Patel *et al.* (2006b) |
| Atrazine + metribuzin 0.5 + 0.15 kg/ha | Sandy loam | 7.8 | 89.3 | Middle Gujarat | Patel et al. (2006b) |

farmers are using atrazine year after year. Thus, it is desirable to employ tank mix combinations of two herbicides having different modes of action in order to widen the weed control spectrum. A number of tank mix combinations of atrazine with pendimethalin, alachlor, metolachlor, metribuzin, 2,4-D *etc*. were tried in different research experiments under different agro-climatic conditions with weed control efficiency of 80, 67-97, 90-94, 89, and 53-67%, respectively (Table 3). Likewise, alachlor also tank mixed with a number of herbicides like pendimethalin, metolachor, metribuzin etc. proved to be successful in controlling the hardy weeds with weed control efficiency of more than 80% (Table 5).

Atrazine, recommended as a pre-emergence herbicide, is not effective against some of the weeds, both grassy and non-grassy as well as the sedge *Cyperus rotundus*. Also, sometimes farmers skip the application of pre-emergent herbicides and also due to the scarcity of labour at that time, there is left no other alternative to control the weeds emerging during later stages. However, recently a pigment synthesis inhibitor tembotrione (42% SC), which is a post-emergent broad spectrum systemic herbicide of triketone group has been tested and proved to be successful in managing all the categories of weeds infesting the maize fields during later stages. Singh *et al*. (2012) from Pantnagar reported that post-emergence application of tembotrione 120 g/ha along with surfactant (1000 ml/ha) was found most effective to control the grassy as well as non-grassy weeds as compared to other herbicidal treatments either applied as pre- or post-emergence with maximum weed control efficiency (90%). Efficacy of tembotrione 42% SC formulation increases when used with surfactant against mixed weed flora compared to when used alone (Table 7). Similar results were reported by Akhtar (2014) in spring maize at SKUAST-Jammu. Kannan and Chinnagounder (2013) from TNAU, reported that post- emergence application of potassium salt of glyphosate at 1800 g/ha in transgenic and conventional maize hybrid of 30V92 enhanced the complete control of broad spectrum weeds and hence significantly lowered weed density, weed dry weight and higher weed control efficiency ranging from 96-99% (Table 8 ).

Continuous use of herbicides at high doses reduces efficiency, develops resistance in weeds and leaves residues in the environment to toxic levels. However, The application of low dose herbicides reduced the quantity of herbicides, required for weed control along with hand weeding is the key practice for environmental stewardship and herbicide mixtures may serve the need for broad spectrum weed control besides long term and economic management for farmers. Rani *et al.* (2011) reported that application of sulfosulfuron 15 g/ha + imazethapyr 25 g/ha as pre-emergence with hand weeding at 40 DAS was found to be effective and economic weed management practice for irrigated sweet corn during *Rabi* season in sandy loam soils of southern agroclimatic zone of Andhra Pradesh. However, in areas where timely labour availability is

**Table 4. Use of pendimethalin in maize-based cropping systems in different agro-ecologies**

| Herbicide/dose | Soil parameters | | WCE (%) | Location | References |
|---|---|---|---|---|---|
| | Soil | pH | | | |
| Pendimethallin 1.50 kg/ha | Clay loam | 5.6 | 60.5 | Palampur (mid-hiils), HP | Kumar *et al.* (2012) |
| Pendimethallin 0.50 kg/ha | Sandy loam | 7.8 | 76.5 | Middle Gujarat | Patel *et al.* (2006a) |
| Pendimethalin 1.0 kg/ha | Loamy sand | | 71.5 | Ludhiana, Punjab | Walia *et al.(* 2007) |
| | Clay | 7.4 | 76.7 | Navsari, Gujarat | Arvadiya *et al.* (2012) |
| | Medium to deep black | 6.5-7.5 | 36.5 | Bijapur (rainfed), Karnataka | Singh *et al.* (2009) |
| Pendimethalin *fb* atrazine 1.50 *fb* 0.75 kg/ha | Clay loam | 5.6 | 75.2 | Palampur (mid-hiils), HP | Kumar *et al.* (2012) |
| Pendimethalin 0.9 kg/ha + 2,4-D (sodium salt) 0.5 kg/ha at 30 DAS (*Rabi*) | Clay | - | 50.3 | Junagarh, Gujarat | Dobariya *et al.* (2014) |

**Table 5. Use of alachlor in maize/maize-based cropping systems in different agro-ecologies**

| Dose | Soil parameters | | WCE (%) | Location | References |
|---|---|---|---|---|---|
| | Soil | pH | | | |
| Alachlor 1.0 kg/ha | Sandy loam | 7.8 | 70.3 | Middle Gujarat | Patel *et al.* (2006b) |
| Alachlor 2. 0 kg/ha | Medium to deep black | 6.5-7.5 | 45.6 | Bijapur (rainfed), Karnataka | Singh *et al*. (2009) |
| Alachlor 2.5 kg/ha | Loamy sand | - | 74.4 | Ludhiana, Punjab | Walia *et al.(*2007) |
| Alachlor + metolachlor 0.5 + 0.5 kg/ha | Sandy loam | 7.8 | 81.0 | Middle Gujarat | Patel *et al.* (2006b) |
| Alachlor + pendimethalin 0.5 + 0.25 kg/ha | Sandy loam | 7.8 | 81.0 | Middle Gujarat | Patel *et al.* (2006b) |
| Alachlor + metribuzin 0.5 + 0.15 kg/ha | Sandy loam | 7.8 | 80.4 | Middle Gujarat | Patel *et al.* (2006b) |

**Table 6. Integrated weed management in maize/maize-based cropping systems in different agro-ecologies**

| Dose | Soil parameter | | WCE (%) | Location | References |
|---|---|---|---|---|---|
| | Soil type | pH | | | |
| Alachlor 2.0 kg/ha + 1 HW at 30DAS | Medium to deep black | 6.5-7.5 | 55.6 | Bijapur rainfed, (Karnataka) | Singh *et al. (*2009) |
| Atrazine + pendimethalin *fb* 1 HW 0.50 + 0.50 kg/ha | Loamy sand | - | 86.7 | Ludhiana, Punjab | Walia *et al.*(2007) |
| Atrazine + alachlor *fb* 1 HW 0.50 + 0.75 kg/ha | Loamy sand | - | 89.4 | Ludhiana, Punjab | Walia *et al.(*2007) |
| Atrazine + trifluralin *fb* 1 HW 0.50 +0.60 kg/ha | Loamy sand | - | 84.9 | Ludhiana, Punjab | Walia *et al. (*2007) |
| Atrazine 0.5 kg/ha + 1 HW and IC at 30 DAS (*Rabi*) | Clay | - | 63.4 | Junagarh, Gujarat | Dobariya *et al.* (2014) |
| Pendimethalin 0.9 kg/ha + 1 HW and IC at 30 DAS *(Rabi*) | Clay | - | 51.1 | Junagarh, Gujarat | Dobariya *et al.* (2014) |
| Sulfosulfuron 30 g/ha as pre-emergence + HW at 40 DAS(*Rabi*) | Sandy loam | 7.4 | 73.4 | Tirupati, AP | Rani *et al.* (2011) |
| Imazethypyr 50 g/ha as pre-emergence + HW at 40 DAS(*Rabi*) | Sandy loam | 7.4 | 71.5 | Tirupati, AP | Rani *et al.* (2011) |
| Sulfosulfuron 15 g/ha + imazethaypyr 25 g/ha as pre-emergence with HW at 40 DAS (*Rabi)* | Sandy loam | 7.4 | 88.8 | TirupatiAP | Rani *et al.* (2011) |

assured, hand weeding twice at 20 and 40 DAS may be followed. Tank mixtures of atrazine with pendimethalin, alachlor or metribuzin along with hand weeding were tried in different research experiments under different agro-climatic conditions with weed control efficiency of 50-89% (Table 6). Walia *et al.* (2007) reported that the application of atrazine + alachlor 0.50 + 0.75 kg/ha *fb* 1 HW proved to be significantly superior with highest weed control efficiency of 89.4% followed by atrazine + pendimethalin 0.50 + 0.50 kg/ha *fb* 1 HW and atrazine + trifluralin 0.50 + 0.60 kg/ha *fb* 1 HWwith the corresponding values of weed control efficiency of 86.8 and 84.9%, respectively.

**Residual effect of herbicides:** Chemical weed control is the best supplement to conventional methods and forms an integral part of the modern crop production. Most of the available herbicides provide only a narrow spectrum weed control. Moreover, mixtures of herbicides allow a wider spectrum of weed control with total active ingredient. Mixture of herbicides is recommended for each crop and in the cropping system, sequential application of herbicides for each crop leads to residue accumulation in the soil and crop, thus causing adverse effects on succeeding crops. Most of the herbicides are selective and specific to the crop and persist in the soil for a few months to a few years depending upon the chemical and concentration used. Knowledge of the persistence and residual effect of herbicides in the soil is essential to use them safely and effectively. Bioassay remains a major tool for qualitative and quantitative determination of herbicides in soil. The new weed management technology based on environmental principles uses "environment-friendly" herbicides, mainly glyphosate and glufosinate. These herbicides have little residual activity, are low in mammalian toxicity, and have an average half-life in soil of about 40-60 days. This means little restriction for crop rotation and low environmental degradation (Pacanoski 2006). Verma *et al.* (2009) from Kanpur conducted an experiment to assess the direct and residual effects of atrazine with regard to weed growth and crop growth of maize-green gram cropping system and reported that atrazine applied in maize had no residual effect on weed emergence and crop stand of succeeding greengram. Likewise, Patel *et al.* (2006) from Gujarat reported that pre-emergence application of pendimethalin 0.25 kg/ha either with atrazine or alachlor or metolachlor each 0.5 kg/ha or metribuzin 0.15 kg/ha recorded significantly lower density of monocot and dicot weeds at all the intervals and also recorded higher grain yield of maize as compared to all other treatments.

None of the herbicides applied alone or as mixture at tested rates had an adverse effect on succeeding *Rabi* oat and mustard crops. However, the use of some new herbicides belonging to the sulfonylurea group like sulfosulfuron, mesosulfuron + iodosulfuron *etc*. are reported to have some residual activity. The sulfonylurea herbicides though applied at very low rates but are known for their residue under varied type of environmental conditions because of less dissipation rates (Pandey and Singh 1994). Sulfonylurea herbicides are highly active in the soil and some crops in rotation can be sensitive to even low soil residues (Walker and Brown 1982), additionally, excessive mobility and persistence of herbicides in soils may cause groundwater

**Table 7. Bio-efficacy of new molecules against mixed weed flora in maize in different agro-ecologies in India**

| Dose | Soil parameters | | WCE (%) | Location | Reference |
|---|---|---|---|---|---|
| | Soiltype | pH | | | |
| Tembotrione + surfactant 120 g/ha + surfactant (1000 ml/ha) at 15-20 DAS | - | - | 90.3 | Pantnagar | Singh *et al.* (2012) |
| Tembotrione 120 at 15-20 DAS | - | - | 74.1 | Pantnagar | Singh *et al.* (2012) |
| Sulfosulfuron 30 g/ha as pre-emergence (*Rabi*) | Sandy loam | 7.4 | 13.0 | Tirupati (AP) | Rani *et al.* (2011) |
| Imazethaypyr 50 g/ha as pre-emergence (*Rabi*) | Sandy loam | 7.4 | 14.0 | Tirupati (AP) | Rani *et al.* (2011) |

**Table 8. Effect of glyphosate application on total weed density and weed control efficiency in conventional maize transgenic hybrids**

| Transgenic hybrid | Herbicide application | Soil parameters | | WCE (%) at 40 DAS | Location | Reference |
|---|---|---|---|---|---|---|
| | | Soiltype | pH | | | |
| 30V92 | POE glyphosate 900 g/ha | | | 96.15 | | |
| 30V92 | POE glyphosate 1350 g/ha | | | 97.66 | | |
| 30V92 | POE glyphosate 1800 g/ha | Sandy | | 99.14 | | |
| 30B11 | POE glyphosate 900 g/ha | clay loam | 8.11 | 95.86 | Coimbatore | Kannan and |
| 30B11 | POE glyphosate 1350 g/ha | | 8.31 | 97.17 | | Chinnagounder (2013) |
| 30B11 | POE glyphosate 1800 g/ha | | | 98.87 | | |
| 30V92 | PE atrazine 0.5 kg/ha | | | 68.96 | | |

contamination and phytotoxic effects to sensitive crops grown in the following season. Balyan (1998) also reported that with the exception of 0.4 mg glufosinate on mung bean and soyabean, the three herbicides, 0.4 or 0.6 mg/litre of sulfosulfuron, chlorosulfuron or glufosinate were phytotoxic and decreased weed dry matter in all the crops i.e. mung bean, soyabean, pearl millet, maize and sorghum. Also, Yadav *et al*. (2004) reported that the sulfosulfuron 25 g/ha and pendimethalin 1500 g/ha applied in wheat caused toxicity to maize but not to mung bean and cotton. However, Kaur and Brar (2014) from PAU, Ludhiana conducted a study to assess the residual effects of sulfosulfuron (25, 37.5 and 50 g/ha) and mesosulfuron + iodosulfuron (12, 18 and 24 g/ha) herbicides applied to wheat on maize (*Zea mays* L.) grown in sequence and reported that none of the sulfonylurea herbicides applied to wheat at different doses affected the emergence of maize crop during both the years. But the effect was evident on the growth characters and yields of maize during 2005, whereas in 2004, plant height and dry matter at all the stages of maize was not affected significantly. This might be due to the difference in rainfall received at different stages of the crop growth in both the years. Hence, it is not safe to grow maize in rotation after application of these sulfonylurea herbicides on wheat, as significant effect on the growth and yield of maize was recorded during the years of less rainfall.

## Future thurst areas

The review revealed that there is significant scope of application of herbicides though the current challenge is to manage herbicides and other inputs in such a manner that prevents adapted species from reaching troublesome proportions. Other major areas of future thrusts include:

*Assessment of on-farm losses caused by weeds:* The yield losses caused by weeds in different maize-based cropping systems in the farmer's field at different agro-ecological regions needs to be assessed.

*Weed ecology:* To achieve maximum possible benefit from weed management technologies, sophisticated technical research must be conducted in weed ecology, genetics and physiology to enhance the basic understanding of the processes that regulate weed-crop interactions, weed population dynamics, adaptation and persistence under various weed management practices. Weed management should have a primary focus on practices that affect propagule production and survival mechanism within the diverse agro-ecosystems.

*Interdisciplinary effort:* To tackle the complex weed problem, research must involve system analysis, weed community analysis, molecular biology, assessment of pre and post shifts in weed community, herbicide resistance issues, issues related to transgenic plants, environmental issues and potential benefit of weeds.

*On-farm assessment of weed management options:* The weed management options identified by researchers must be tested in the farmer's field to assess their effectiveness and economic viability. Despite decades of research and extension in popularizing the weed management practices, its effectiveness and importance are not completely understood and hence are less adopted by the farmers. Thus, a closer linkage between researchers and extension functionaries is needed for evolving weed management strategies and popularizing effective and economical options with the farming community.

*Need for knowledge-based decision-making tools:* There is a need to develop a larger database of weed ecology and biology characteristics, and also to develope improve and refine weed management system simulation models for extension work and for predicting further areas where research is required. An area of current concern is the carry over residual studies of herbicides in different maize-based cropping systems. We still don't have broad spectrum post-emergent herbicides as by and large the pre-emergence application of atrazine has remained a sole destination for the past many years towards herbicidal weed management in maize. Some new molecules like tembotrione and halosulfuron have shown some promise in post-emergence control, but still have limitations with respect to complete vegetation control. There is a need to develope single window herbicide: remote sensor based remotely sensed *in situ* instant weed management technology. Also the uses of allelochemical-based herbicides is still a far-fetched hypothesis for weed management practices.

The challenge for weed scientists is to develope effective, innovative, and environmentally safe weed management system that can be integrated into current and future maize-based cropping systems to bring a more diverse approach to weed management.

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