PERSPECTIVE

Sustainable Weed Management Options for Potato (*Solanum tuberosum* L.) Cultivation in Assam

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Abstract

Potato (*Solanum tuberosum* L.) is an economically important tuber crop in Assam, in which weeds can cause productivity losses of up to 80%. This article reviews some effective weed-control techniques for growing potatoes in Assam, developed as part of the "*Potato Knowledge Bank*" of the *International Potato Centre* (CIP). During a potato's vegetative growth, many types of weeds can significantly reduce both yields and tuber quality. Managing weeds, using different methods, is, therefore, a major component of the potato production process. Under most conditions, the critical period of weed competition for potatoes is about 25-30 days from planting.

In potato cultivation, it is important to minimize weeds before the crop emerges using an approach of Integrated Weed Management (IWM). This requires choosing fast-growing, high-yielding potato varieties, planting the crop at the right time and maintaining an ideal plant population in the fields. Added to this list are various cultural practices, which include land preparation, harvesting at the right time, the timing and placement of farmyard manure (FYM) and fertilizers, and the incorporation of green manure crops. Suitable crop rotations can also result in effective weed control in potato fields. The 'stale seed bed' technique is one of the best options for potatoes because it has the potential to reduce human labour and weed management costs. Soil solarization can also be a simple, safe, cost-effective and eco-friendly technology to control weeds.

Chemical weed control is also a significant component of IWM for potatoes. Molecules, such as the soil-applied, photosynthetic inhibitor – Metribuzin, are widely used for this purpose. Rice straw or water hyacinth biomasses could effectively be used as a mulching material to control weeds over conventional modes of cultivation. Potato Production through Zero-Tillage with Paddy Straw Mulch is also a highly effective way to manage weeds in potato fields.

Keywords: potato production, weed management, mulching, zero tillage

Introduction

Potato (*Solanum tuberosum* L.) is one of the important food crops in the world. Among root and tuber crops, potato ranks top, followed by cassava (*Manihot esculenta* Crantz.), sweet potato [*Ipomoea batatas* (L.) Lam.] and many other yams in terms of volumes of global production and consumption. Potato is globally produced in 140 countries (FAOSTAT, 2020) and ranks fourth in production, following wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), and rice (*Oryza sativa* L.).

Potato has been consumed by the Incas in the Andes for about 8,000 years and was brought to Europe by the Spanish in the 16th Century. From a South American origin, potatoes then quickly spread across the globe.

Today potatoes are grown on an estimated 193,000 km^2 of farmland, from China's Yunnan plateau and the sub-tropical lowlands and temperate highlands of India to Java's equatorial highlands and the steppes of Ukraine (FAO, 2009) [1].

Potato is also ranked as the first most important 'non-grain' crop in the world. In 2020, 16.5 million hectares (ha) around the world had been planted with potatoes, with a production of >359 million tons (FAO, 2009; FAOSTAT, 2020). Its importance for global food security was internationally recognized when the UN made "*2008 - the Year of the Potato*" (FAO, 2009) [2].

According to the FAO (2009), "*Food security exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life.*" Food security, therefore, has four key dimensions: (a) food availability (b) quality and use (c) stability and (d) accessibility to food. The '*humble potato*' is regarded as a high-potential, '*food security crop*' because of its ability to provide a high yield per unit area during a relatively short crop cycle of fewer than 120 days (FAO, 2009).

Potato's production cycle is shorter than those of major cereal crops, such as maize and grain sorghum [*Sorghum bicolor* L.) Moench] (FAO, 2009). Potato, as a food product, is also highly valued because it essentially contains all the nutrients necessary for human nutrition (carbohydrates, proteins, vitamins and minerals) and is so-highly palatable in various preparations (Burgos et al., 2020; Ahmadu et al., 2021). In modern-day food industries, various types of potato products (French fries, potato chips, mashed potatoes, etc.), as well as ready-to-eat products (pasteurized potato) and processed foods (peeled potato in vacuum packaging, etc.), are widely consumed by populations of many countries (Burgos et al., 2020; Ahmadu et al., 2021).

From the 1960s, cultivation of the potato expanded in the developing world. In India and China alone, total production rose from 16 million tonnes in 1960 to 100 million in 2007. In North-Eastern India and Bangladesh, potatoes have become a valuable winter cash crop, while potato farmers in South-East Asia have tapped into the exploding demand for it from food industries. In sub-Saharan Africa, potato is a preferred food in many urban areas, and an important crop in the highlands of Cameroon, Kenya, Malawi and Rwanda (FAO, 2009).

The potato has an extraordinarily rich past, steeped in ancient civilizations (Incas in South America), colonialism (14th to 16th Centuries) and a bright future. While production in Europe – the potato's "second home" for four centuries – is declining, the potato has ample room for expansion in the developing world, where its consumption is less than a quarter of that of developed countries. Today in many mountainous regions of Africa, farmers are shifting from maize to potato, assisted by the FAO with virus-free seed tubers (FAO, 2009).

In the Peruvian Andes, where the potato's journey across the world began, the Government of Peru created in July 2008 a national register of Peruvian native potato varieties, to help conserve the country's rich potato heritage. That genetic diversity, the building blocks of new varieties adapted to the world's evolving needs, will help write future chapters in the story of *Solanum tuberosum* (FAO, 2009).

In India, potato is cultivated on about 2203 ha, producing a national average of 56,173 and 53,575 metric tons (MT) in 2020-21 and 2021-22, respectively (Ministry of Agriculture, 2021-22). As in all countries and regions that grow potatoes (FAO, 2009; FAOSTAT, 2020), potato production in India has also undergone many changes in the way the crop is grown. Research over several decades in both temperate countries and sub-tropical regions, such as North-Western and North-Eastern India, has shown that various factors in the field affect potato's optimal growth and development. These include soil type, climate, water, nutrients and sunlight availability.

Managing weeds, pests and diseases is also critical in potatoes as they are a particularly sensitive crop before their canopy develops (Nelson and Thoreson, 1981; Nelson and Giles, 1989). Weed

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[1] While the Incas called it papa (as do modern-day Latin Americans), the Spaniards called the potato *patata*, confusing it with another New World crop, the sweet potato (known as *batata*). In 1797, the English herbalist *John Gerard* (c. 1545–1612) referred to the sweet potato as "common potatoes", and for many years *Solanum tuberosum* was known as the "Virginia potato" or "Irish potato" before finally displacing batata as the potato (FAO, 2009, p. 17).

[2] The UN's Food and Agriculture Organization (FAO) released *New Light on a Hidden Treasure*, a 144-page illustrated book in 2008, which recorded the achievements of the *International Year of the Potato*. The essential message was that the potato is a vital part of the global food system and will play an ever greater role in strengthening world food security and alleviating poverty. The review also provided the most recent FAO statistics on world potato production and consumption, and profiles of 52 major potato producing countries.

management in potatoes requires an integrated weed management (IWM) approach and also a change in how weeds are perceived. Weeds should be managed in a holistic, intentional and proactive manner.

Understanding the interactions between the potato crop and the weed community is important to discourage weeds; maintain a low weed seed or propagule bank and for sustainable weed management in potato cultivation systems.

This article provides a perspective on sustainable options for weed management in potatoes, based on Indian experiences. At the *International Centre for Potato* (CIP, 2022) [3], the focus was especially on potato cultivation in Assam, a State in north-eastern India (**Figure 1**). Potato is a widely cultivated crop in Assam. It is the second most important crop in all districts of Assam, although the State contributes only a relatively small, 1.41% of the national potato production in India (Ministry of Agriculture, 2021-22).

Recently, the author has been involved in developing a *knowledge Bank* for Potato cultivation in Assam, now available through the CIP (2022). This article reviews some of the existing knowledge about potatoes and their relationship with weeds, with a focus on improving sustainable weed management and increasing potato yields, particularly in Assam but also applicable in other Indian States.

Potato Cultivation in Assam

The State of Assam, in North-Eastern India, is located south of the eastern Himalayas, along the Brahmaputra and Barak River valleys. It extends from 89° 42′ E to 96° E longitude and 24° 8′ N to 28° 2′ N latitude. Assam has an area of 78,438 km^2, which is similar to Ireland or Austria (**Figure 1**). Assam shares borders with Bhutan and Bangladesh and is surrounded by the States of Arunachal Pradesh, Nagaland, Manipur, Mizoram, Tripura and Meghalaya. Together with Assam, these are called India's *Seven Sister States*. The majority of the Assamese population resides in the vast Brahmaputra valley in the north, amidst numerous mountains, streams and rivulets from the nearby hills.

Potato productivity in Assam is between 7-10 tons ha^{-1}, which is very low compared to India's national average of about 23 tons ha^{-1} (Ministry of Agriculture, 2021-22). This significantly lower production output of potatoes in Assam is attributed to low potato seed availability and low seed quality, as well as inadequate scientific knowledge of potato cultivation and pest and disease management.

As a result of low production and the large gap between demand and supply, Assam imports potatoes from neighbouring states, such as West Bengal, Meghalaya, Uttar Pradesh (UP) and Punjab, every year. The *Assam Agri-business and Rural Transform* (APART) is a program established to develop a potato value chain in Assam to benefit farmers including addressing constraints and through farmer support to overcome them. It is carried out with support from the *International Potato Center* (CIP) which provides consultancy services to the Government of Assam.

Assam is ranked 8th in potato production among the Indian States (Ministry of Agriculture, 2021-22) and much effort is underway to increase potato production with options, including improved varieties and cultural practices (CIP, 2022). The major potato-growing districts in Assam are Karbi Anglong, Cachar, Hailakandi, Jorhat, Lakhimpur, Golaghat, Sivasagar, Kamrup, Kokrajhar, Morigaon, Darang, Nagaon, Nalbari, Barpeta, Sonitpur, Majuli, Bongaigaon, Dhemaji and Biswanath Chariyali (**Figure 1**), which account for about 75% of production (CIP, 2022).

In Assam, potato is planted between two paddy cultivation seasons i.e. *Sali* (from June/July–Nov/Dec) and *Boro* (from Nov/Dec to June/July). Therefore, the available time for potato cultivation is only about 70 to 90 days. The region requires varieties that can mature in 80-100 days and can tolerate the potato late-blight disease (caused by the fungal-like oomycete pathogen [*Phytophthora infestans* (Mont.) De Bary] [4].

[3] The *International Potato Center* (CIP) was founded in 1971 as a research and development organization with a focus on potato, sweet potato and Andean roots and tubers. It delivers innovative science-based solutions to enhance access to affordable nutritious food, foster inclusive sustainable business and employment growth, and drive the climate resilience of root and tuber agri-food systems. Headquartered in Lima, Peru, CIP has a research presence in more than 20 countries in Africa, Asia and Latin America, working with partners, including national and regional research institutes, civil society, academia and the private sector (CIP, 2022).

[4] The Late blight fungus causes sudden plant death and destroys infected potato crops in a matter of days. It attacks the potato foliage, fruit, stems or tubers at all growth stages. Healthy looking potato tubers may also break down in storage due to late blight infection.

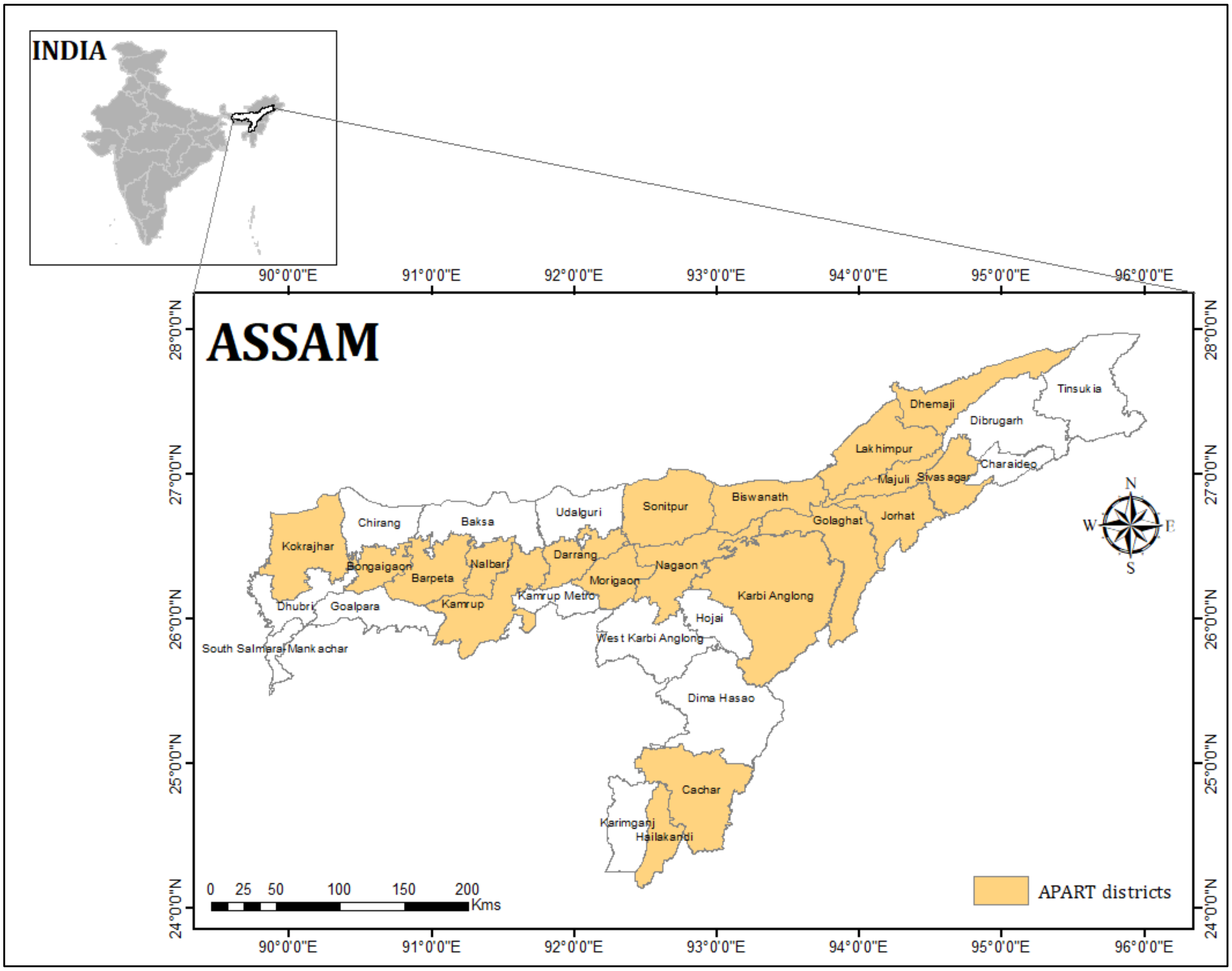

Figure 1 Map showing the location of Assam State in North-Eastern India

The most suitable varieties also need to have the capacity to tolerate drought and also have good keeping quality. The suitable planting time for potatoes is from October to mid-December when night temperatures fall below 20 ^{0}C.

The recommended table-purpose potato varieties and those suitable for processing are summarized in **Table 1**. The most popular varieties for cultivation are selected by farmers according to climatic conditions, market demand and resistance to diseases. **Figure 2** and **Figure 3** show some potato fields in Assam.

As a cool season crop, in Assam, potato is planted when the maximum temperature is less than 30°C. The optimum day/night temperatures for potato growth are 28/12°C. The optimum night temperature in Assam for tuber growth is between 10-15°C. The highest average yields are obtained where the day length is 13-17 hours (CIP, 2022).

Figure 2 A typical potato field – early growth

Figure 3 A potato field with maturing crop growth

Higher soil temperatures adversely affect tuber development, which virtually stops if temperatures rise above 30°C. Sunshine, along with cooler nights, is essential for reducing the spread of potato diseases. While well-drained sandy loam and medium loam soil are best for potato cultivation, soils rich in organic matter with good drainage and aeration are also suitable and can be used.

Slightly acidic soils (pH 5.5-6.5) are ideal for growing potatoes. The incidence of common scabs in Assam tends to be less of a problem where soil pH is below 5.4 for susceptible varieties. The common scab of potatoes is a soil-borne disease, widespread in the world, caused by the bacteria-like organism *Streptomyces scabies* Lambert and Loria. The bacterium attacks both potato tubers and stems.

Table 1 Potato Cultivation in Assam – A summary

Potato cultivation area: 103,812 ha 14.74% of the total area under horticultural crops of the State			Assam occupies a geographical area of 7.8 million ha of which the total cropped area is 4.0 million ha. However, only 5.4% of the gross cultivated area is irrigated. Assam's average farming land holdings are very small; only 0.63 ha, compared to India's National average of 1.10 ha. Farm families in Assam: about 27.5 lakhs of which small and marginal farm families account for 85.3%
Popular Cultivars #	**Duration**	**Production Tons ha^{-1}**	**Characteristics**
Kufri Surya (T)	80-90	25-30	Heat tolerance, blight tolerance, very good keeping quality
Kufri Pukhraj (T)	70-80	35-40	Poor blight resistance, early bulking, high yield
Kufri Jyoti (T)	80-90	25-30	Blight tolerance, good keeping quality
Kufri Himalini (T)	80-90	25-30	Blight tolerance, good keeping quality, high yield
Kufri Khyati (T)	70-80	30-35	Poor blight tolerance, and early bulking. high yield
Kufri Lima (T)	80-90	25-30	Blight and heat tolerance, good keeping quality
Kufri Mohan (T)	70-80	35-40	Moderately blight resistance, early bulking
Kufri Karan (T)	80-90	25-30	Blight and virus tolerance, good keeping quality
Yusi Maap (T)	80-90	25-30	Blight, drought and virus tolerance, good keeping quality
Kufri Chipsona-3 (P)	90-100	25-30	Blight tolerance, good keeping quality, high dray matter
Lady Rosetta (P)	90-100	25-30	Blight susceptible, good keeping quality, high dry matter
Atlantic (Pvt) (P)	90-100	25-30	Blight susceptible, good keeping quality, high dry matter
Taurus (Pvt) (P)	90-100	25-30	Blight susceptible, good keeping quality, high dry matter
Columba (Pvt) (T)	80-90	25-30	Blight susceptible, good keeping quality, early bulking

Source: Potato "Knowledge Bank" (CIP, 2022); T – Table varieties; P – Processing varieties

A common practice is to lower the soil pH to be in the range of 5.0 to 5.4 to manage the common scab disease. Harvesting potatoes at soil temperature >20°C is known to increase the risk of microbial rotting, especially of damaged tubers (CIP, 2022).

A well-pulverized seedbed is required for good tuberization of potatoes. In Assam, the common field bed preparation involves the use of a mould-board plough, followed by two to three cross harrowings, using a disc harrow rotavator (**Figure 4**) or cultivator to plough the fields up to 20-25 cm. One or two plankings are also used to level the surface. Most farmers use a rotavator one week before potato planting to further loosen the soil (CIP, 2022).

Figure 4 Loosening the soil by using a rotavator one week before potato planting

In fallow lands, newly converted to potato, green manuring with Indian hemp (*Crotalaria juncea* L.) or yellow pea bush [*Sesbania cannabina* (Retz.) Pers; syn. *Sesbania aculeata* (Willd.) Pers.] is undertaken during the rainy season. These species "fix" nitrogen through root nodules. A dry biomass of 4-5 tons ha^{-1} of the legumes can add 80−100 kg N ha^{-1} to the fields. When buried about one month before potato planting, the decomposing green manure reduces pest and disease incidence and also improves soil fertility and the soil's water-holding capacity (CIP, 2022).

Potato is also cultivated under the cover of plastic sheets (Pszczółkowski et al., 2020; Mohaniya et al., 2020), or polythene film in various countries, particularly in Western and Eastern Europe, to provide the plants with appropriate thermal and humidity conditions and reduce the risk of spring frost damage. This practice is common in other Indian States (Mohaniya et al., 2020; Gupta et al., 2020) but not common in Assam because of the costs involved in purchasing plastic sheets.

Losses caused by Weeds in Potato

Crops and weeds compete for space, light, water, nutrients, and other resources during the growing season (Zimdahl, 1980; 1987). The competitiveness of a weed community depends on the species' composition, time of emergence and abundance. Yield losses are usually high when weeds emerge earlier or at the same time as the crop and are minimized if they emerge later than the crop. Prevailing environmental conditions also influence the outcome of weed-crop interactions (Zimdahl, 1980).

Weed infestations are one of the most important limiting factors in the production of potatoes in Assam. In potatoes, weed infestations are favoured by a wide row spacing, a long period from planting to plant emergence, the potato's slow initial growth and the use of organic manures and mineral fertilization (CIP, 2022). As a consequence, many cultural practices and influential factors need to be modified to obtain better potato yields and profits for farmers.

When abundant, broad-leaf weeds (dicotyledons), grasses and sedges (monocotyledons) can deplete the resources available for the potato crop. Some may also interfere with potato growth by releasing allelochemicals or by harbouring harmful insects and pathogens. Apart from affecting yields, weeds reduce the quality, size and weight of potato tubers (Nelson and Thoreson, 1981; Atiq et al., 2009; Azadbakht et al., 2017; Soren et al., 2018; Gugała et al., 2018; Barbaś et al., 2020; Yadav et al., 2021).

The Critical Period of Weed Competition in potato

The critical period of weed competition is approximately 1/3rd of the duration of most crops, including potatoes. The severity of yield loss depends on weed infestation, duration of infestation and climatic conditions, which affect the growth of both weeds and crops (Zimdahl, 1980; 1987).

The critical period of weed competition is the shortest time during the crop's growth when weeding results in the highest economic returns. The crop yield level obtained by weeding during this period is almost similar to that obtained by the full season weed-free conditions. It is also the period of crop growth when the crop must be kept weed-free to prevent yield loss due to weed interference (Zimdahl, 1987).

Bleasedale (1965), in an early article, explained how the early growth of weeds affects potato growth and yields. In India, Mani et al. (1968) reported potato yield losses of 25-35% and Saghir and Markoullis (1974) reported a 58% yield loss when weeds competed for the full season with potatoes. In their studies, early-season weed presence was not detrimental unless weeds remained in the plots past 6-9 weeks after potato planting.

Zimdahl (1980) pointed out that these results disagreed with those reported from Java, Indonesia, by Everaarts and Satsyati (1977) who found that if potatoes were kept weed-free for the first four weeks after planting, they experienced no yield losses. In the Java study, under zero weed control, the yield loss in potatoes was 22% compared with 'weed-free' plots (Everaarts and Satsyati, 1977).

Different potato varieties can compete effectively with annual broad-leaf weeds in particular and their competitive ability correlated with early emergence, rapid early growth and maintenance of a dense leaf canopy throughout the growing period. However, it is well-known that, as a crop, potato does not possess vigorous early competitiveness.

In some early studies, Baziramakenga and Leroax (1994) found that to achieve 90% of the highest possible potato tuber yield, the maximum time permitted for weeds to grow after potato emergence was 15 days. They also found that the same level of tuber yield could be obtained if the crop was kept free of weeds from its emergence until 23–68 days.

Baziramakenga and Leroax (1994) also showed that perennial quackgrass [*Elytrigia repens* (L.) Nevski], at a density of 25 stems m^{-2}, caused a 10% potato tuber yield reduction in Quebec, Canada. The studies of Ciuberkis et al. (2007) in Lithuania found that the 20 cm potato height was the most important stage affecting potato yield loss due to weed competition. Potato yield losses were minimized when weeds were removed before potatoes reached 20 cm or were kept clean from this point forward. The results indicated that the critical weed-free period when weed competition was detrimental to yield started from planting and lasted until 25 days after flowering.

Research in India and Assam has shown that in most situations, the critical period of weed competition for potatoes is 25-30 days from planting (CIP, 2022). However, the global literature indicates that, broadly, the potato crop should remain weed-free for up to 40-50 days depending upon the farming situation, which can vary widely. Delayed weeding until late stages could result in irreversible damage due to weed competition. Therefore, effective weed control is crucially important to obtaining high tuber yield.

Potato plants tend to drop between ridges after 65-70 days of planting as the crop matures and at this stage, the second flushes of weeds thrive. These may not cause significant damage to tuber productivity but play a role in increasing the soil's weed seed bank while hindering harvesting the crop (Singh et al., 2018b). Nelson and Giles (1989) also pointed out the importance of not neglecting the weed flora that must be controlled to reduce the intensity of competition in future crops in the fields used for potatoes.

Major Weeds of Potato fields and Yield Losses

As with most other crops, weeds compete with crop plants for nutrients, soil moisture, space and sunlight. Weeds also serve as an alternate host for several insect pests and diseases. Weed competition can reduce potato quality, affecting tuber size, weight and quantity (Ahmadu et al., 2021). Weeds also interfere with mechanical harvest options in potatoes (Singh et al., 2018b).

Uncontrolled weed growth can reduce tuber yield by about 18-82% depending on the types of weeds, their abundance and the duration of the competition (Singh et al., 2002; Ciuberkis et al., 2007, Kumar et al., 2009; Soren et al., 2018; Ahmadu et al., 2021). In recent studies in Ludhiana, North-West India, Shafique and Kaur (2021) reported that uncontrolled weed growth resulted in 50% potato yield losses.

Weeds interfere with harvest, causing more potatoes to be left in the field and increasing mechanical injury. In some early studies in the USA, Nelson and Thoreson (1981) reported that if annual weeds and perennial weeds compete with potatoes all season, each 10% increase in dry weed biomass could cause a decrease of up to 12% in tuber yield.

According to Azadbakht et al. (2017), Soren et al. (2018) and Barbaś et al. (2020), potato yield losses due to weed infestation in Europe are estimated to be 10% to 70%. These estimates are highly variable and include losses resulting from direct competition with weeds, as well as the host role of weeds relating to diseases and pests, harvest difficulties, mechanical damage and deterioration of the quality of the harvested potato. Caldiz et al. (2016) reported even higher losses, up to 95% potato tuber yield reduction, depending upon the potato variety, the infesting weed species and the crop-weed competition period.

In India, 10% potato yield losses due to weeds in potatoes were estimated to result in production losses of INR 40 million (CPRI, 2021). The wider row spacing, frequent irrigation, and use of organic manures and fertilizers favour the early emergence of weeds before potato tubers germinate, causing yield losses by 40-65% or even more in some cases (Singh et al., 2002; Mohaniya et al., 2020; CIP, 2022).

In studies at India's *Directorate of Weed Research* (DWR) in Jabalpur, Madhya Pradesh (MP), Chethan et al. (2019) reported that the potato plots were heavily infested with burr clover (*Medicago denticulata* Willd.), followed by wild oat (*Avena fatua* L.), toothed docks (*Rumex dentatus* L.), sowthistle (*Sonchus* L.

sp.), figleaf goosefoot (*Chenopodium ficifolium* Sm.), lamb's quarters (*Chenopodium album* L.) and small canary grass (*Phalaris minor* Retz.). In potato trials at Gwalior (MP) in India, Gupta et al. (2020) reported purple nutsedge (*Cyperus rotundus* L.), lamb's quarters and small canary grass as the major weeds (38%, 25% and 18%, respectively of the flora) while several other annual and perennial grasses and broad-leaf weeds formed the remainder. Working at *ICAR-Central Potato Research Station* (1740 m above mean sea level), based at Shillong, Meghalaya, in Northern India, Yadav et al. (2021) reported a similarly mixed weed flora comprising common broad-leaf weeds and grasses, as well as sedges (i.e. *Cyperus cyperiodes* (L.) Kuntz).

In Assam, Baruah and Sarma (1994) reported a total of 33 weed species in potato fields belonging to different families. Lamb's quarters, carpet grass [*Axonopus compressus* (Sw.) Beauv.] and Bermuda grass [*Cynodon dactylon* (L.) Pers.] were the dominant weeds. **Table 2** gives the most predominant weed species found in potato crops in Assam, which can appear in the fields before potato emerges. Sedge weeds were less prevalent in Assam compared to other Indian States (CIP, 2022).

Table 2 Important weeds associated with potato in Assam

Common name	Scientific name	Family
Grasses		
Carabao grass	*Paspalum conjugatum* P.J. Bergius	Poaceae
Barnyard millet/Barnyard grass	*Echinochloa crusgalli* (L.) P. Beauv.	Poaceae
Bermuda grass	*Cynodon dactylon* (L.) Pers.	Poaceae
Rice grass	*Leersia hexandra* Sw.	Poaceae
Glenwood grass	*Sacciolepis indica* (L.) Chase	Poaceae
Swamp millet	*Isachne globosa* (Thunb.) Kuntze	Poaceae
Torpedo grass	*Panicum repens* L.	Poaceae
Indian goosegrass	*Eleusine indica* (L.) Gaertn.	Poaceae
Broad-leaf weeds		
Giant sensitive weed	*Mimosa diplotricha var. Innermis* C. Wright	Fabaceae
Giant sensitive weed	*Mimosa pudica* L.	Fabaceae
Shiny bush	*Peperomia pellucida* (L.) Kunth	Piperaceae
Sisso spinach/Joyweed	*Alternanthera sessilis* (L.) DC	Amaranthaceae
Jersey cudweed	*Pseudognaphalium luteoalbum* L.	Asteraceae
Floss flower	*Ageratum houstonianum* Mill.	Asteraceae
Indian-field cress	*Rorippa indica* (L.) Hiern	Brassicaceae
Lamb's quarters/fathen	*Chenopodium album* L.	Amaranthaceae
Common knotweed	*Polygonum plebieum* R.Br.	Polygonaceae
Winged false button weed	*Spermacoce alata* Aubl.	Rubiaceae
Spreading dayflower	*Commelina diffusa* Burm.f.	Commelinaceae
Chocolate weed	*Melochia corchorifolia* L.	Malvaceae

Weed species growing in potato fields can also harbour plant pathogens, although information on this aspect is lacking from Assam and also, more broadly from India. Nevertheless, reporting from Cameroon, Fontem and Olanya (2003) recorded the potato late blight pathogen *Phytophthora infestans* on some common weeds in potato fields, such as *Polygonum alatum* (D. Don) Buch.-Ham. ex Spreng. [renamed, *Persicaria nepalensis* (Meisn.) H. Gross], purple morning-glory [*Ipomoea purpurea* (L.) Roth] and sowthistle (*Sonchus oleraceus* L.).

The pathogen of potato bacterial wilt, *Ralstonia solanacearum* Smith, was also found on Billy goat weed (*Ageratum conyzoides* L.), green amaranth (*Amaranthus viridis* L.) and seed-under-leaf (*Phyllanthus niruri* L.) growing in and around potato fields (Fontem and Olanya, 2003).

Weed Management Methods in Potato

The production process of potatoes comprises 'best practice' cultivation and weed management. The methods most commonly used are well-documented from temperate and sub-tropical countries, with some local differences (Atiq et al., 2009; Azadbakht et al., 2017; Chethan et al., 2019; Barbaś et al., 2020).

Research over decades has shown that the main objective of managing weeds in potatoes should be to decrease weed abundance to below the economic threshold level with minimum damage to the crop and its growing environment. The literature shows that cultural practices, including a well-planned crop rotation, planting cover crops, sanitation practices, optimum row spacings and timing of planting are important aspects of managing weeds in potatoes. Multiple, well-timed shallow cultivations, either by using simple implements or mechanically operated ploughs, can eliminate many early-season weeds during land preparation. Once emerged, some potato varieties grow fast and produce a canopy, which can suppress weeds (CIP, 2022).

Our surveys indicate that, as with most crops, the choice of effective weed control strategies for potatoes in Assam is influenced by the severity of predicted weeds and their abundance in cultivation areas. Nevertheless, how Assamese farmers manage weeds and the methods they use are influenced by their socio-economic conditions and local constraints of related agricultural enterprises.

The following sections describe the weed control methods deployed in Assam in potato production and include various cultural practices, as well as mechanical and chemical control, aiming to reduce yield losses due to weeds.

Cultural Weed Control Methods

Potato varieties and Seeding rate

Weeds in potatoes can be suppressed during the initial phases of potato growth by way of crop competition. This requires fast-growing and high-yielding varieties, timely planting, higher seed rate and maintaining the optimum plant population in the fields (Boydston and Vaughn, 2002; CIP, 2022). Cultivars that emerge fast after planting and grow fast to develop a strong canopy, can either suppress weeds or tolerate weed competition. This is an important component of an Integrated Weed Management (IWM) system for potatoes. Cultivar tolerance of weed competition is directly related to emergence timing and canopy closure during the early season.

Such cultivars would reduce the reliance on herbicides for weed control in potatoes. Nevertheless, crop competitive ability has not been a focus of potato plant breeding efforts, or indeed in many other vegetable crops. As a result, the competitive ability of some new potato cultivars has decreased over time (Colquhoun et al., 2009). Our surveys have also found that the impetus to adopt cultivar competitiveness against weeds, as a management tactic in potatoes has been minimal, in India and elsewhere. A possible reason is the success of pre-emergent, soil-applied herbicides in reducing weed populations.

In Assam, farmers conduct timely management of cultivation - from land preparation to harvesting – as a component of 'best practices' to suppress weeds and also minimize crop-weed competition. If seeding rates are insufficient, an optimum potato crop population cannot be achieved, which leads to heavy weed infestations, and the emergence of species that are difficult to manage. However, weeds emerging from under a fast-growing crop canopy are generally weak and do not always reduce tuber productivity.

Typically, virus-free, healthy, 35-45 mm (B) grade size, sprouted seed tubers are planted and the seeding rate depends on seed size and planting geometry when using inter-row distances of 60 cm and seed-to-seed distances of 20 cm (**Figure 5** and **Figure 6**). The preferred seed weight of full or cut tubers with 2-3 sprouting 'eyes' for seeding is 35 gm (i.e. approximately, 83,000 tubers per ha). Potato crops are usually planted 8-12 cm deep, on ridges (45-60 cm apart) or on loose soil and flatter surfaces, in shallow furrows (CIP, 2022).

Field preparation

The importance of tillage using cultivators and harrows, and seedbed preparation with raised beds ('hilling'), in growing potatoes successfully, has been long established (Nelson and Giles, 1989; Boydston and Vaughn, (2002). However, excessive cultivation can increase soil erosion, especially in hilly areas, increase soil compaction, and bring weed seeds to the soil surface (Nelson and Giles, 1989). Some planting failures in Assam are due to poor tuber sprouting or lack of germination caused by an incorrect planting depth and poor seed bed preparation.

Figure 5 A proper planting geometry (planting distance) of a potato field in Assam

Figure 6 Sprouted seed tubers

A well-pulverized seedbed is important for good initial germination of seed potato and the tuberization of potato as the crop matures. In Assam, deep ploughing of the field up to 20-25 cm is optimal and can be achieved by using a mould-board plough, followed by two or three cross harrowings, using a disc-harrow cultivator. One or two plankings are also needed to make the surface smooth and level.

The final soil preparation is done by a rotavator a week before potato planting. These primary and secondary operations help in destroying existing weeds and preventing others from germination. Pre-plant tillage operations for making a proper soil tilth will also accelerate the potato's faster emergence, giving it a competitive advantage (CPRI, 2021).

Generally, the potato crop is raised in a wider planting geometry. The method of hand-broadcasting manures and fertilizers is common in small and marginal farms in Assam. It is not advantageous because it encourages weed growth all over the field. Further, frequent irrigation also benefits the early and faster-emerging weeds (CPRI, 2021).

A common practice in Assam is the application of well-decomposed farmyard manure (FYM) at a rate of 20-25 tonnes ha^{-1}, combined with N-P-K fertilizer at the rate of 125-100-125 kg ha^{-1}, placed in bands 5-6 cm below the seed tubers. These placements ensure that the nutrient inputs remain in the potato's root zone, allowing the crop to utilize the nutrition more effectively and speed up its vegetative growth.

Crop rotation

Crop rotation has been a long-standing method in cropping, especially to reduce pests and diseases and the build-up of weed populations in cropping fields, as well as to replenish soil nutrients, such as nitrogen. If the same crop is grown year after year, there is a greater chance that a particular weed species or a weed community will begin to dominate in that field.

Diversified crop rotations can prevent such weed flora changes by varying planting dates and the length of the growing season and by the weed control practices associated with each crop. A diversified crop rotation is also the basis of preventing many soil-borne pests and pathogens from developing into levels that can harm a crop.

For Assam, at least a two-year crop rotation is generally recommended as a '*Potato-Mung-Paddy'* rotation, in which the rice is transplanted. This rotation can be implemented on suitable fields that can be irrigated for the rice. An alternative is a green manure crop (sun hemp, dhaincha) rotated to smother weeds and add nutrients for a succeeding potato crop.

Stale seedbed

A stale seedbed is one where the initial one or two flushes of weeds are destroyed before planting a crop. This is achieved by soaking a well-prepared field with irrigation or rain and allowing weeds to germinate. At this stage, shallow tillage or non-residual herbicides, such as paraquat or glyphosate could control flushes of young weed seedlings, which allows potatoes to germinate in an almost weed-free environment. The stale seedbed is seen as an '*eco-friendly*' method for weed control as it kills weeds before the planting of the crop. It also depletes the weed seed bank in the surface layer of the soil (Senthilkumar et al., 2019).

Soil Solarization

Soil solarization is a method that uses solar energy for the destruction of weed seeds. In this method, the soil temperature is further raised by 5–10ºC by covering a pre-soaked fallow field with a thin transparent plastic sheet. The plastic sheet reduces the long-wave 'back' radiation from the soil and prevents energy loss by hindering moisture evaporation. Solarization of soil has been reported to manage weeds and control nematodes, soil-borne diseases and insects (Singh et al., 2018).

‘Earthing up’ and Mulching

‘Earthing-up’ is essential in potato cultivation to keep the soil loose, control weeds, and for firming up the ridges to prevent exposure of the growing tubers. The first earthing-up is usually done when the plants are about 15-25 cm high with a small canopy (25-30 days after planting). In Assam, earthing-up is done by using hand tools like Khurpa and spades.

Hoeing, bullock-drawn mould-board plough or tractor-drawn two- or four-row ridges can also be used for earthing-up. Sometimes, a second earthing-up is done to cover up the tubers more effectively, two weeks after the first. Fertilization with a split dose of N is also done simultaneously while earthing-up. Delaying these cultivation operations beyond 30 days after planting runs the risk of damaging the developing potato roots, foliage and stolons (CIP, 2022).

Plant-based mulches

Mulch, placed on the soil surface, protects the soil. It also physically prevents weed seed germination. Decomposing plant mulches also release inhibitory compounds, which can kill weed seeds (Mahmood et al., 2002; Teasdale and Mohler, 2008; Barman et al., 2009; Razzaque and Ali, 2009; Bhullar et al., 2015).

Working in India, Gupta et al. (2020) showed that dried or green crop residues - straw from rice or other cereals- can be effective in potatoes, against annual weeds and even some perennial grasses and sedges. Other researchers (Shafique and Kaur, 2021; Liu et al., 2023) have reported that plant-based mulches are most effective in potatoes when they are used in combination with herbicides. Plant-based mulches reduce the surface soil temperature and also prevent moisture loss from the soil surfaces, which helps potato growth (Sadawarti et al., 2013; Pulox et al., 2016; Azadbakht et al., 2017; Sarangi et al., 2018).

To effectively control weeds from germinating and prevent weed seedling establishment, the mulch covering should be sufficiently thick (about 15-20 cm thick). Paddy straw, applied at about 10-12 tons ha^{-1} (4-5 kg of rice straw/m^2), provides a cover of a 15-20 cm thick layer. For mulching one *bigha* of the zero-tillage potato crop, rice straw from three bighas can be used. Potato plants come out of the rice straw in 15-20 days and rapidly grow to cover the entire available area. Weed growth is practically nil due to the thick rice mulch (Brijesh Kumar et al., 2022).

Added advantages of using straw mulches are that when they slowly decompose, they add organic matter to the soil, increasing both nutrients and the soil’s water-holding capacity. The growth of soil microbes is also greatly stimulated by decomposing plant residues used as mulches. Bhullar et al. (2015) and Shafique and Kaur (2021) reported improved weed control with the application of rice straw mulch at the sowing time at 6 tonnes ha^{-1} of potatoes.

Water hyacinth [*Eichhornia crassipes* (Mart.) Solms] is ranked among the top-ten weeds worldwide. Water hyacinth multiplies fast and due to its negative impacts, it is popularly known as the ‘*Beautiful Blue Devil*’. Its vast growth and coverage of water surfaces adversely affect navigation, fishing, recreational usage of water bodies, and hydropower generation. Manual harvesting and some forms of mechanical removal are the most common method of control of water hyacinth, especially in developing countries.

In Assam, water hyacinth is abundant in almost every water body, extending from large lakes to household ponds in rural areas. For a long time, water hyacinth was considered only as waste, which is cleaned up from waterways and left to decompose, unused. In recent decades, however, dried water hyacinth biomass has become popular as mulch that can be used in potato cultivation, as well as growing other vegetable crops. However, to be most economically viable, the utilization of water hyacinth mulch needs to occur near the source of origin.

The adoption of dried water hyacinth mulch, under rainfed conditions, increases potato tuber yields. Water hyacinth mulch can be applied to cover the entire field after planting tubers under the flatbed method (**Figure 7** and **Figure 8**). The skin of the tubers may turn green due to exposure to sunlight or shrinkage of mulching materials on drying. Tubers become unsuitable for consumption upon greening. However, this undesirable effect may be reduced by applying the mulch in furrows just after planting tubers, immediately followed by a light soil cover. Such practices also reduce rodent damage to tubers considerably (AAU, 2019; CIP, 2022).

In studies conducted at the DWR, in Jabalpur (Barman et al., 2008), both rice straw and water hyacinth mulches controlled weeds well throughout the growing period of potatoes. In the presence of mulches, there was no additional benefit from herbicides (Metribuzin at 0.25 or 0.5 kg ha^{-1}) in terms of weed control or tuber yield. Moreover, there was a 40% increase in potato yield in plots mulched with water hyacinth, compared with rice straw. In Bangladesh, Razzaque and Ali (2009) also confirmed that different potato varieties differed in their responses to rice straw and water hyacinth mulches under no-till conditions. However, higher tuber yields were recorded under the water hyacinth mulch treatments.

Figure 7 A water hyacinth-mulched field after planting of potato

Figure 8 Emergence of the potato crop in water hyacinth mulching after one month

Plastic Mulches

Mulching with black plastic has been shown to improve potato stem number, plant height, and yield (Bharati et al., 2020). Black plastic mulches were reported to have increased soil temperature, reduced weed competition, improved nutrient uptake, and improved soil moisture regimes, which resulted in more large-sized tubers being produced (Ibarra-Jiménez et al., 2011).

Compared to black and white plastic mulch, silver plastic mulch had a greater PAR (photosynthetically active radiation) reflectance, and such increased PAR reflection by silver plastic mulches lowered root zone temperature, resulting in optimum soil temperature and reducing water loss (Amare and Desta, 2021). Plants grown under black plastic mulch retained the highest soil temperature but showed a marginal difference only in yield compared with control plants (Ibarra-Jiménez et al., 2011).

Among the various mulching materials tested, films of silver on black plastic and black plastic have been the most effective in increasing tuber yields (Aryal et al., 2023). Research in China (Li et al., 2018) showed that mulching with black plastic film is an effective practice for winter potato production. It increased the soil temperature and was more suitable for potato emergence and tuber bulk in winter potato production. Mulching has a positive effect on microclimates and maintains a better growing environment, which is imperative for increasing potato yields.

Herbicides

Chemical weed control is a significant component of weed management in potatoes and has a long history dating back to the 1960s and 70s in the USA and other developed countries (Nelson and Giles, 1989; Ackley et al., 1996; Robinson, et al., 1996; Renner and Powell, 1998; Caldiz et al., 2016). Herbicides act much quicker against weeds in potato and present an advantage because potato is a relatively short-duration crop.

Herbicides in potatoes can be applied over large areas in a short time with minimal labour costs (Baranowska et al., 2016; Gugała et al., 2018; Barbaś and Sawicka, 2020; Yadav et al., 2021). Many soil-applied herbicides, such as EPTC, linuron, metolachlor, metribuzin and rimsulfuron have long been used in potato cultivation in the USA and elsewhere (Bellinder et al., 2000; Yadav et al., 2021).

Metribuzin has long been a standard component of pre-emergence (PRE) and post-emergence (POST) weed management programs in potatoes because it is effective on many broadleaf weeds and grasses (Friesen and Wall, 1986; Ackley et al. 1996; Robinson et al., 1996; Wilson et al., 2002). However, heavy reliance on metribuzin in potato cultivation in the USA shifted weed species to those that are metribuzin-tolerant within a few decades, resulting in inadequate weed control in potato cultivation.

Following this, in an important study in the USA, Renner and Powell (1998) showed how the major weeds in potatoes can be well managed with PRE and POST applications of rimsulfuron, metribuzin, and mixtures of rimsulfuron plus metribuzin. PRE applications of rimsulfuron at 27 g a.i. ha^{-1} and POST applications at 18 g a.i. ha^{-1} controlled barnyard grass [*Echinochloa crus-galli* (L.) Beauv.], redroot pigweed (*Amaranthus retroflexus* L.), and wild buckwheat

(*Polygonum convolvulus* L.). Common lamb's quarter (*Chenopodium album* L.) was controlled by PRE or POST applications of metribuzin or a tank mixture of 18 a.i. ha^{-1} rimsulfuron plus 140 a.i. ha^{-1} of metribuzin. The variety '*Russet Burbank*' potato was relatively tolerant to all of the herbicides and the mixtures, and potato yield was not reduced compared to the hand-weeded control (Renner and Powell, 1998).

In other studies in the USA, Tonks. and Eberlein (2001) showed that the sulfonylurea- rimsulfuron rates of 9, 18, 26, or 35 g ai ha^{-1} achieved effective weed control with little potato injury (less than 5% across all rimsulfuron rates) when applied post-emergence, in combination with various adjuvants- i.e. nonionic surfactant (NIS), crop oil concentrate (COC), methylated seed oil (MSO), or silicone-polyether copolymer (SIL). In general, a host of common weeds were controlled by 75-93% and tuber yields increased with better weed control (Tonks. and Eberlein, 2001).

In the USA, past research has shown that cultivation alone may reduce weed competition with potatoes but may also result in tuber damage, as well as reduced harvesting efficiency from increased weed presence at harvest. Given the sensitivity of potato varieties, the use of PRE applications of metribuzin and POST applications of rimsulfuron, either alone or in combination with other soil-applied herbicides, has now become almost standard practice.

In combination with timely cultivations, applications of PRE and POST herbicides are an essential component of growing potatoes profitably in the USA, especially if the fields are infested with difficult-to-control weeds, such as yellow nutsedge (*Cyperus esculentus* L.) and a wide spectrum of broadleaf weeds and grasses (Bailey et al., 2001; 2002).

In related studies, Wilson et al. (2002) showed that sulfentrazone and flumioxazin were selective and safe when applied to many potato varieties and controlled many weeds common in potato fields in the USA. They also reported evidence that both herbicides were much more effective than metribuzin and could also be used in combination with other chemistries (such as metolachlor) to provide a broader spectrum of weed control (Wilson et al., 2002).

In parts of Europe (Poland), potato production relies heavily on mechanical weed control combined with various combinations of herbicides. Barbas and Sawicka (2020) showed that PRE applications of Metribuzin (0.5-1.0 kg ha^{-1}), PRE and POST applications of the sulfonyl-urea herbicide Rimsulfuron or similar, and POST applications of the selective grass-killer Fluazifop for controlling grasses, were highly effective. Herbicides could increase the potato yield by as much as 60% and Metribuzin alone stood out as being the most effective, resulting in yield increases of up to 50% (Barbas and Sawicka (2020).

Globally, the list of both PRE and POST herbicides approved for use in potatoes is quite extensive (**Table 3**). In India, too, herbicides to manage weeds in potatoes have become popular because of their ease, economic benefit and effective control of the weeds (Kumar et al., 1998; Mishra et al., 2002; Singh et al., 2007; Choudhury et al., 2016; Sondhia, 2018; Chethan et al., 2019; Yadav et al., 2021; Chaudhary et al., 2022; Chandel et al., 2022).

A few PRE, pre-plant incorporated (PPI) or POST herbicides are registered for potatoes in India. Choudhury et al. (2016) and Chaudhary et al. (2022) showed that the commonest ones used in India include Metribuzin, 2,4-D amine, Prometryne and Paraquat. Others, used occasionally in some States are Pendimethalin, Fluchloralin and Oxyfluorfen.

In some Indian States, research is focused on PRE applications of Prometryne (1.0 kg ha^{-1}) with a half-rate of Metribuzin (0.5 kg ha^{-1}), which gives the control of a broad range of weeds without affecting tuber yields (Chaudhary et al. (2022).

Paraquat use, as a 'knock-down', non-selective, contact-action herbicide is common in many crops in India, including potatoes. This is partly because it is more affordable to farmers and the fast-acting effects on weeds are visible within hours of application (Chandel et al., 2022).

However, Metribuzin 70% WP, at 0.5-1.0 kg/ha, applied in 500 L of water, as a pre-plant and early PRE application, has long been the principal herbicide used to control both mono- and dicotyledonous weeds in potatoes in India (Choudhury et al., 2016). In other countries, where paraquat is banned, diquat (Reglone ®) is used as a substitute. Although under certain conditions, metribuzin damages some potato varieties, under Indian conditions, and in Assam, PRE application of metribuzin 70% WP at the rate 0.75 kg a.i. ha-^{1} or 100 g/big ha (1 Big ha=13.37.80 m^2) in moist soil effectively controls a range of broadleaf weeds and suppresses the growth of many types of grasses. Chethan et al. (2019) recently reported that the application of Metribuzin at 0.75 kg/ha as PE effectively controlled most weeds and reduced the weed densities to 2.43 and 2.04 weeds/m^2. The corresponding reduction in the weed dry biomasses were 1.35 and 1.64 g/m^2 respectively at 25 and 55 DAP with a resultant and increased potato tuber yield.

Table 3 Herbicide commonly used for Potato – India and Other Countries*

Herbicide (Trade Name)	Application and Herbicide Mode of Action (MOA)	Usage
Alachlor (Lasso ®) #	PRE applications, 1.0 kg/ha applied in 500 L/ha; Lipid synthesis (long-chain fatty acids) inhibitor.	Global and in some Indian States
Clomazone (Command ®)	Soil applied or PRE before potato emerges for annual broad-leaf weeds; pigment synthesis inhibitor.	Australia, New Zealand, Europe
EPTC (Eptam ®)	Pre-plant incorporated; 1-2 kg/ha; Lipid synthesis inhibitor.	Global
Fluazifop-butyl (Fusilade ®)	Post-emergence, selective grass control; lipid synthesis inhibitor [acetyl CoA (ACCase) enzyme inhibitor].	USA, Europe
Fluchloralin (Basalin ®)	Pre-plant incorporated; 1.0 kg/ha; a dinitro-aniline group herbicide, disruptor of microtubule assembly	Global, including India
Flumioxazin (Chateau ®,Valor ®)	cell membrane disruptor and Inhibitor of protoporphyrinogen oxidase (PPO) enzyme.	USA
Methabenzthiazuron (Tribunil ®)	PRE applications of 2.5-3.0 kg/ha in 340-450 L of water before potatoes emerge; photosystem-II inhibitor.	Global and in some Indian States
Metolachlor (Dual ®; Magnum ®)	Lipid synthesis (long-chain fatty acids) inhibitor.	Global and in some Indian States
Metribuzin (Sencor ®)	Most commonly used as PRE (1.0 kg/ha in 500 L/ha); also used as POST interrow application; photosystem-II inhibitor.	Global, including India and Assam
Oxadiazon (Ronstar ®)	0.75 kg ha^{-1}; Inhibitor of protoporphyrinogen oxidase (PPO) enzyme.	Global and in some Indian States
Oxyfluorfen (Goal ®; Rout ®)	PRE applications of 100-200 g $ha^{-1;}$ Inhibitor of protoporphyrinogen oxidase (PPO) enzyme.	Global and in some Indian States
Paraquat dichloride # (Gramoxone ®, Ozone ®)	Bi-pyridinium; Non-selective, contact herbicide, Pre-plant or interrow applications; fast-acting photosynthesis inhibitor.	Global, including India
Pendimethalin (Stomp ®)	PRE applications, 1.8 kg/ha applied in 500 L/ha; a dinitro-aniline group herbicide, disruptor of microtubule assembly.	Global, including India
Prometryne (Gesagard ®; Bandit ®)	PRE applications of 1.0 kg ha^{-1}; a triazine herbicide, causes Inhibition of photosynthesis at photosystem II.	Global, including India
Trifluralin (Treflan ®) #	PRE applications of 1.0 kg ha^{-1}; a dinitro-aniline herbicide, disruptor of microtubule assembly in cells; often applied in mixture with metribuzin for broad-spectrum weed control.	Global, including India
2,4-D Amine	Phenoxy acid herbicide; Mostly PRE but occasionally used as POST inter-row applications before potato emerges.	Global, including India
Diquat (Reglone ®) #	Bi-pyridinium; Non-selective, contact herbicide, Pre-plant or interrow applications; fast-acting photosynthesis inhibitor.	USA, Australia, New Zealand, Europe
Rimsulfuron (Titus ®, Matrix ®; Resolve ®	PRE or POST applications; amino acid synthesis inhibitor [acetolactate synthase (ALS) enzyme inhibitor].	USA, Australia, New Zealand, Europe
Sulfosulfuron (Apyros ®)	PRE or POST applications; amino acid synthesis inhibitor [acetolactate synthase (ALS) enzyme inhibitor].	USA
Sulfentrazone (Spartan ®)	Soil-applied to control broad-leaf weeds and sedges; cell membrane disruptor.	USA

*Sources: (1) India (**http://agropedia.iitk.ac.in/content/chemical-weed-control-potato-crop**); (2) Mishra et al., 2002; Singh et al., 2007; Choudhury et al., 2016; Sondhia, 2018; Chandel et al., 2022); (3) Europe: Barbas and Sawicka, 2020; ** Only metribuzin is used in Assam, mainly because of the cost, which is INR 1500/ha.

*** All POST applications use adjuvants, such as Crop Oil concentrates (COC) or methylated seed oil (MSO), or silicone-polyether copolymer (SIL); # Paraquat and Alachlor are banned in India; Trifluralin is limited to uses in wheat only; the bans and prohibitions have come into effect since 31 December 2020 (Choudhury et al., 2016). Diquat is preferred to paraquat in some countries.

Adding to these findings, working at *ICAR-Central Potato Research Station* (1740 m above mean sea level), based at Shillong, Meghalaya, in Uttar Pradesh (UP), Yadav et al. (2021) recently confirmed that the most effective weed control was obtained by a combination of hand-weeding with a PRE or POST (at 10% potato emergence) application of Metribuzin (0.75 kg ha^{-1}). and a second POST application of Metribuzin, at the same rate, at 10% of potato emergence. The effectiveness of the treatments gave high potato tuber yields (about 20 tons ha^{-1}) and an income of INR 176,000 ha^{-1}.

Although the use of herbicides is quite limited in Assam, significant amounts of herbicides are used in other States of India, as indicated by literature (Choudhury et al., 2016; Chaudhary et al., 2022). In Assam, only Metribuzin is recommended as PRE applications at 1.0 kg ha-1 applied in 400-500 L ha-1 of water. Metribuzin costs INR 1500 per ha and for most farmers, this is considered affordable relative to the profits from potatoes. In potato cultivation trials at Jabalpur, Sondhia (2002) reported that metribuzin applied at 0.85 and 1.20 kg ha^{-1} persisted up to the harvest time in black soil and also noted that under Indian conditions, metribuzin remained active in the soil for even up to 100 days (Sondhia, 2018).

Colquhoun et al. (2009) noted that site-specific weed management has limited application in potatoes, which have traditionally relied heavily on preemptive herbicide applications to control weeds during the period when the crop is not competitive. However, an overall reduction in herbicide use can be achieved by developing cultivar-specific management strategies. These can combine herbicide use with competitive characteristics, such as rapid emergence and early growth rate and canopy closure. In Assam, it is particularly important to adopt reduced herbicide strategies that should be based on (1) competitive cultivars, (2) a combination of banded PRE herbicides and cultivation, and (3) selective POST herbicides.

Presently, there is not much data on herbicide-resistant weeds in potatoes in Assam. This is because herbicide use is rather limited. However, as herbicides are commonly used in potatoes in other Indian States, there is awareness of the need to prevent herbicide-resistant weeds from developing in potato fields. In other countries, this is done by crop rotations and by using different herbicide mixtures and combinations and changing the regimes of herbicides approved for potatoes. Other methods include applying herbicides to weeds when they are young and most sensitive; applying non-selective herbicides (such as paraquat, diquat or glyphosate), before potato emerges, at rates that guarantee a complete kill.

IWM and Conservation Agriculture (CA) Practices

Conservation Agriculture (CA) is popular in India, as a means of reducing herbicide use and other high-energy inputs for agriculture. CA aims to minimize soil disturbances and retain healthy soil, allowing crop intensification at the same time (Das et al., 2018). Competitive crop varieties are of vital importance in CA, although in potatoes and many other crops, breeding for CA-responsive, specific varieties are yet to make much headway (Das et al., 2018).

With CA approaches, mono- and double-cropping systems are now changing to double- and triple-cropping systems, through Zero-Tillage (ZT) with paddy straw mulch use in potato production in Assam. The practices were introduced for the first time in seven Districts of Assam in 2018-19 and in 14 Districts during 2019-21, as a component of the CIP-APART *Potato Value Chain Program* (CIP, 2022).

In this practice, potato is sown immediately after the *kharif* rice harvest without any further tillage or soil preparation. As a result, there is an efficient use of residual soil moisture, as well as an estimated saving of 10-12 days used otherwise for soil preparation. The zero tillage with paddy straw mulch technique, introduced primarily as a climate-resilient technology, is gaining popularity among potato farmers. It uses paddy straw as a mulching material and ensures water saving (Bhullar et al., 2015; Das et al., 2018).

Recent studies by Mohaniya et al. (2020) at Gwalior, Madhya Pradesh (MP) showed that the highest potato yields and profits were obtained from two rounds of hand weeding at 20 and 40 days after planting (DAP), followed by one hand-weeding at 20 DAP + Straw mulching @ 5 t ha^{-1} at 25 DAP. When labour is scarce, farmers choose the second option or even resort to using only the straw mulching option, applied early at five DAPs (Mohanty et al., 2020).

Studies in Assam have shown that when the potato field is covered with 15-20 cm thick paddy straw, it protects the soil from drying under warm conditions and long days with bright sunlight (**Figures 9-11**). The straw effectively reduces weed emergence, especially broad-leaf weeds, by 90-100%. The straw mulch also reduces the incidences of pests and diseases (99 % reduction in damage by cutworms), and lower post-harvest potato losses and costs of cultivation (CIP, 2022). The general cost of a 15-20 cm thick paddy straw mulch layer in Assam is about INR 6000 ha^{-1}, without the labour costs of mulching it.

Figure 9 Raised bed potato mulching with paddy straw

Figure 10 A typical zero tillage potato with paddy straw mulch field after two months

Mahmood et al., (2002) and Zaman et al. (2009) reported that under paddy straw mulch, potatoes recorded higher yields than other cereal mulches. Paddy straw mulching gave higher yields and net returns and also recorded higher water use efficiencies (WUE) over no mulching (Sadawarti et al., 2013). Mulching increases the system efficiency, cropping intensity and farmer’s profit thus helping in achieving the goal of doubling farmer's income.

In recent studies, Sarangi et al. (2018) reported higher tuber yields of 20.7 tons ha^{-1} under zero tillage with 12 tons ha^{-1} of paddy straw mulching plus foliar sprays of nutrients for potatoes. The Zero tillage method of potato cultivation is particularly suitable for salt-affected coastal regions as well mainly because early harvesting is possible and another short-duration pulse crop, such as green gram can be grown in rotation. The cropping intensity increase can yield profits of up to 300 % (rice-potato-green gram) than with potato cultivation alone (CIP, 2022).

Figure 11 Zero tillage potato produced under mulching with paddy straw at harvest

Conclusions and Future Outlook

At the End of Year of the Potato (2008) review, the FAO's Director General Jacques Diouf said that "*The potato is on the frontline in the fight against world hunger and poverty*" (FAO, 2009). CIP's engagements with the Assamese potato farmers indicate that this statement is valid in Assam too, as most farmers consider potatoes to be a cash crop that can provide quick profits and also alleviate hunger and poverty.

Ahmadu et al. (2021) recently explained that "*peculiar features of potato crop such as its adaptation range coupled with high nutritional value and production ease have aroused the interest of many people to embark on its cultivation*". This interest is present in the whole of North-Eastern India too and has led to steady increases in potato production and consumption. However, in Assam, production constraints, including the management of weeds, pests and pathogens have limited the capacity of the State to produce sufficient quantities of potatoes.

The literature on potato cultivation is expansive already and is increasing as cultivation is popular in many developed and developing countries as it is a short-duration cash crop. Despite potatoes being susceptible to a host of pests and pathogens, and weed infestations, in the last few years, there has been an increase in the production of potatoes and their demand in all of Asia, many parts of Africa, and Latin America. FAO Data (FAOSTAT, 2020) show that production increased from less than 30 million tons a few decades ago to more than 360 million tons in 2020 and 376 million tons in 2021 (**Table 4**).

As the two most populated countries in the world, China and India are the biggest global potato producers. The data show that millions of farmers in the world depend on potatoes for food as well as cash income. FAO (2009) also views potato as a reliable food security crop that can help ease future turmoil in the world's food supply and demand and "*improve resilience, especially among smallholder farmers by providing direct access to nutritious food and, increased household incomes*" (Ahmadu et al., 2021).

In Assam, as in many other developing countries, the food security challenge is to produce much and waste fewer potatoes through better pre- and post-harvest management. Pre-harvest and post-harvest management in potatoes, including the management of weeds, pests and diseases; as well as storage, processing and value chain efficiency, are much larger problems than in grain cereals and other vegetable foods. Research in Assam and other States of India and elsewhere have clearly shown that the main causes of potato losses are poor crop and harvest management, infested tubers by pests and diseases, a high percentage of small tubers and weather conditions: frost and heavy rains etc.

The increasing awareness about the nutritional, agronomic, and cash-creating advantages potato provides is likely to further increase its status as a global crop, particularly in developing subtropical and tropical countries. The development and adaptation of integrated pest management will be crucial for sustainable and more resilient and profitable potato production in all potato-growing regions worldwide.

In Assam and other States of India, the selection of varieties for rapid emergence and early canopy development in future potato breeding line evaluations is highly recommended. These useful competitive traits could be incorporated by potato breeders into new cultivars while maintaining desirable end-use characteristics. Emphasis should also be given to using biological approaches in weeds and pest management. This will reduce the dependence on insecticides as well as reduce the risk that insect populations develop resistance against insecticides.

The CIP experiences in Assam agree with the observations of Colquhoun et al. (2009) that potato cultivar selection in the near term will most likely continue to be determined based on end-user and consumer-desired quality characteristics and not competitive ability. However, cultivar selection is critically important for practically implementing IWM and reducing the overall reliance on herbicides.

The CPRI (2021) Annual Report provides details of the potato germplasm being conserved, genetic manipulations, breeding and development of disease-resistant and competitive cultivars, as well as those that can utilize nutrients more effectively. The development of hardier varieties without yield penalties is of considerable significance for future potato production in India and elsewhere.

Despite the success of chemicals, well documented in the global literature (Bellinder et al., 2000; Baranowska et al., 2016; Gugała et al., 2018; Barbaś and Sawicka, 2020), the cost of herbicides is a significant barrier to weed management in potato, especially in new cultivation areas. This means that research on inter-row, band applications and the integration of sulfonyl ureas and other soil-applied herbicides with cultural practices is a high priority to improve Assam's potato production.

The benefits of manipulating available mulches for controlling weeds and crop rotations, particularly with pulses and cereal crops, are well recognized in Assam. Nevertheless, the adoption of well-proven practices is severely constrained in Assam by the local socio-economic factors affecting the growers.

Table 4 Some Potato Production Statistics – Top Ten Countries (Source: FAO, 2020)

Country	2020 Metric Tons	2020 Hectares	Country	2021Metric Tons
1. China	78,183,874	4,218,188	1. China	94,362,175
2. India	51,300,000	2,158,000	2. India	54,230,000
3. Ukraine	20,837,990	1,325,200	3. Ukraine	21,356,320
4. Russian Federation	19,607,361	1,178,098	4. USA	18,582,370
5. USA	18,789,970	369,930	5. Russian Federation	18,295,535
6. Germany	11,715,100	273,500	6. Germany	11,312,100
7. Bangladesh	9,606,000	461,351	7. Bangladesh	9,887,242
8. France	8,691,900	214,500	8. France	8,987,220
9. Poland	7,848,600	225,740	9. Poland	7,081,460
10. Netherlands	7,020,060	164,500	10. Egypt	6,902,816
World Total	**359,000,000**	16,500,000	World Total	**376,000,000 (4.9%⇧)**

* FAO Data from 140 potato producing countries (**http://www.fao.org/faostat/en/#data)**.(2) Latest Global Potato Data: (**https://www.potatonewstoday.com/2023/01/21/global-potato-statistics-latest-fao-data-published/**)

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