INTERNATIONAL JOURNAL OF AGRICULTURE & BIOLOGY
ISSN Print: 1560–8530; ISSN Online: 1814–9596
23–0418/2024/31–5–255–366
DOI: 10.17957/IJAB/15.2152
http://www.fspublishers.org

Review Article

Bio-Management of Weeds through Utilization as Value-Added Products: A Review

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Received 06 October 2023; Accepted 21 February 2024; Published 18 March 2024

Abstract

Weed species are problematic because they reduce value of the land, cause hazards, impede water transportation, cause illness to humans and livestock, reduce biodiversity and reduce crop yield (30–55%) and quality of harvested product when infest field crops. Such traits also include production of high biomass and production of phytotoxins. In addition to agroecosystem, about 50% of garasslands are covered by weeds. Chemical weed control is not sustainable due to evolution of widespread herbicide resistance and other hazards associated with chemical use. One alternative for farmers could be the utilization of certain weed species for a beneficial purpose. This has to be done properly to prevent spreading weed seeds to newly cultivated areas. Nutrients and minerals in weed biomass can be returned to the soil when used as green manure or compost and organic mulch in crops, vegetables and fruit trees. Utilization of weeds as compost, organic mulch, hay and silage, bioherbicides, biofuel and other value-added products could be environment friendly alternatives. Weeds also demonstrate significant potential for utilization in dye degradation, papermaking, cellulose production, corrosion inhibition, biosorption, and phytoextraction. Other indirect benefits include reduced use of synthetic herbicides and fertilizers, and improved soil quality. Little information is available on beneficial uses of weeds. This review paper has discussed the available literature regarding the utilization of weeds, and has identified research gaps and deficiencies, which need further research to explore potential of weeds as a source of value-added products.

Keywords: Bio-herbicides; Bio-fuel; Sustainable agriculture; Organic weed control; Weed compost; Weed mulch; Weed hay and silage

Introduction

Weeds are generally considered harmful pests as they adversely affect crop productivity and cause health problems in humans and animals when infest field crops. It is well-documented that about 45% losses in crop production are due to weeds, uncontrolled weed can cause up to 100% yield loss (Abouziena and Haggag 2016; Chauhan 2020). Weed control with herbicides is the miracle of modern agricultural science. However, we are being confronted with herbicide resistance evolution in weeds and persistent concerns about contamination of crop produce due to the long-term use of herbicides, particularly in vegetables. To date 272 herbicide resistant weed species have been found in 100 crops in 72 countries worldwide (Heap 2024). Studies in recent years have revealed that chemical weed control has many hazards including environmental damage, food toxicity, hormesis in weeds and weed resistance (Abbas *et al.* 2016; Khan *et al.* 2016; Nadeem *et al.* 2017; Matloob *et al.* 2020). Therefore, identification and implementation of alternative weed management strategies are crucial for better productivity and sustainability of agroecosystem.

Proper utilization of weeds as value-added products can enhance the income of farmers, an added benefit to control efforts in various agroecosystems. Weeds may have beneficial uses such as manure, compost, soil and water conservation resources, *etc*. Moreover, many weed species

To cite this paper: Abbas T, MA Nadeem, NR Burgos, A Matloob, M Kamran, MK Munir, MTA Kalyar, N Farooq (2024). Bio-management of weeds through utilization as value-added products: a review. *Intl J Agric Biol* 31:355–366

have medicinal properties and could be developed into medicinal products that provide additional income to farmers (Jayasundera *et al.* 2021). With proper attention and planning, identification of medicinal properties of weedy herbaceous plants and their commercialization could be a highly lucrative venture (Stepp and Moerman 2001; Stepp 2004; Chandrasena 2007). This would also make some natural medicines available and affordable to the public (Jayasundera *et al.* 2021). A lot of research is available regarding the medicinal potential of many weedy plants (Stepp 2004; Chandrasena 2007; Jayasundera*et al.* 2021).

Weed biomass can be used as compost for organic crop production. Weed compost has high nutrient contents and the use of weed compost has resulted in increased growth and development of different crop plants (Rai and Suthar 2020; Rai *et al.* 2021). Weeds may also be used as a source of hay and silage because many weedy plants are rich in nutrients, with higher palatability and digestibility than common forages (Khan *et al.* 2013; Tozer *et al.* 2015; Farooq *et al.* 2021). Many weedy plants are allelopathic, gaining dominance over other weeds by producing phytotoxic compounds can become major source of forage for animals in rangelands and pastures (Om *et al.* 2002; Zohaib *et al.* 2016). Bioherbicideswith less environmental impact can be produced from such plants. Previously, some weed plants such as *Miscanthus* spp. and *Arundo* spp. have been explored as feedstock for renewable biofuel (Suganeshwari and Ramani 2014; Vaicekonyte *et al.* 2014; Borah *et al.* 2016; Ogunjobi *et al.* 2016; Ali *et al.* 2020). Weeds can also be used in biochar preparation (Shinde *et al.* 2012), dye degradation, paper making and cellulose production (Chandel and Singh 2011), corrosion inhibition (Ji *et al.* 2012), source of dye (Dayal *et al.* 2008), bioadsorption (Sangita and Bute 2009) and phytoextraction (Hadi and Bano 2009; Mane *et al.* 2013). This article discusses the utilization of weedy plants as value-added products.

Weeds as compost material

Weeds are frequently overlooked as a source of compost by scientists worldwide. Weed management research has been focused on reducing weed population by chemical control; investigations on weed utilization are minimal. Weed biomass is one of the readily available sources of nutrients and organic matter (Table 1) butdid not receive due attention in the past. The favorable climate conditions can lead to the production of huge weed biomass (5–20 t ha^{-1}) depending on weed species. Because of the intensive and exhaustive farming systems in developing countries, the drainage of soil nutrients occurs to a great extent. It leads to an imbalance in nutrients availability, loss of soil fertility and a drastic reduction in crop/soil productivity. Fertility and productivity of the soil can be sustained with integrated nutrient management, and organic manures are the essential component of integrated nutrient management. The concept of organic waste management, particularly weed biomass and its recycling is a low-input on-farm practice for meeting partial nutrients requirements (25%) of plants and sustaining soil health through the improvement of physico-chemical properties and microbial diversity of soil (Prasad *et al.* 2009; Rai and Suthar 2020; Rai *et al.* 2021).

Weed biomass can be composted either in pits or heaps under both aerobic and anaerobic conditions (Nithya *et al.* 2009). Composts prepared from weeds possess more or comparable nutrient contents to cow dung, farmyard manure (FYM), and green manure crops like sun hemp (*Crotalaria juncea* L.) and quick stick (*Gliricidia maculata* Jacq.) with a considerable reduction in the carbon to nitrogen ratio (Chinnusamy *et al.* 2009; Nithya *et al.* 2009; Prasad *et al.* 2009). However, the quality of compost harvested from weeds varies with weed species, and their sole or mixed use. Mahanta and Jha (2009) recorded the highest compost recovery from *Ipomoea carnea* (Jacq.) than water hyacinth *Eichhornia crassipes* (Mart.) and rice (*Oryza sativa* L.) straw. Likewise, more NPK values in compost were obtained from a mixture of *Parthenium hysterophorus* L. and *Echinochloa colona* (L.) compost than individual weed compost (Parmar and Sondhia 2010). Weed compost prepared from *Chromolaena odorata* (L.), *Pa. hysterophorus*, *Eugenia uniflora* (L.) and *Ei. crassipes* showed 1.32–1.64% N, 0.28–0.67% P and 0.93–1.86% K as against the nutrient contents of 0.78% N, 0.34% P and 0.69% K in FYM (Pramod *et al.* 2010). Similar results were also reported by Nithya *et al*. (2010). However, the nutrient supply potential of weed compost also depends on the composting method. For instance, nutrient contents in weed compost prepared with earthworm under aerobic conditions were higher compared to the compost prepared in anaerobic conditions (Nithya *et al*. 2010).

Vermi-composting technology involves the use of earthworms for recycling non-toxic organic waste to the soil. Succulent weeds can be used for vermi-composting to supplement FYM and inorganic fertilizers (Chinnusamy *et al.* 2009; Roy *et al.* 2009; Najar 2017). The quality of vermi-compost depends on earthworm species. Compost recovery and total nutrient contents were the highest in *Ip. carnea* followed by *Mikania micrantha* (Kunth.) and *Pa. hysterophorus* with *Eudrilus* earthworm as the fastest decomposer (Devi and Khwairakpam 2021). It could be due to the differential composting ability of earthworms owing to feed preference and adaptability. Vermi-compost prepared from weed biomass takes only 1.5–2 months compared to 8–12 months required for other farm wastes. Therefore, it can easily replace the FYM-based vermi-compost, which has become scarce due to decreasing on-farm livestock population (Saha *et al.* 2018). Furthermore, Babu *et al.* (2008) reported that several problematic weeds such as *Lantana camara, Pa. hysterophorus, Saccharum munja* and *Ei. crassipes* can be used as a good source of vermi-compost (Table 1).

Worldwide, much emphasis is being paid on integrated nutrient management as a sustainable crop

Table 1: Weed species and their uses as compost, green manure, mulch and vermi-compost in different field crops

Scientific name	Family	Uses	Rate (tha^{-1})	Name of crop	Reference
Ageratum conyzoides L.	Asteraceae	Mulch	5.0-10.0	Rice	Hong *et al.* (2004); Khanh *et al.* (2005)
Avena fatua L.	Poaceae				
Bidens pilosa L.	Asteraceae				
Brachiaria ruziziensis Germ. & C. M. Erard	Poaceae	Mulch	4-8	Rice	Oliveira *et al*. (2014)
Cassia tora L.	Fabaceae	Vermi-compost	1.0-12.5	Wheat, rice, groundnut mungbean	Borah *et al.* (2009); Roy *et al.* (2009); Nithya *et al*. (2010)
Cassia uniflora Mill.	Fabaceae	Compost, green manure	2.6-10.0	Transplanted and direct seeded rice, maize and sunflower	Prasad *et al.* (2009); Denesh and Prasad (2010); Pramod *et al.* (2010)
Centaurea maculosa Lam.	Asteracea	Compost, green manure, mulch	1-2	Rice	Xuan *et al.* (2005)
*Chromolaena odo*rata (L.) King & H. E. Robins.	Asteracea	Compost, green manure, vermi-compost	2.6-10.0	Fingermillet, groundnut, maize, sunflower and rice	Prasad *et al.* (2009); Denesh *et al.* (2010); Pramod *et al.* (2010)
Eichhornia crassipes (Mast.) Solems	Pontederiaceae	Compost, green manure, vermin- compost, mulch	1.0-2.5	Rice, wheat, maize, peanut and mungbean	Borah *et al.* (2009); Roy *et al*. (2009); Nithya *et al*. (2010)
Euphorbia hirta L.	Euphosbiaceae	Mulch	1-2	Rice	Xuan *et al.* (2005)
Ipomoea carnea Jacq.	Convolvulaceae	Vermi-compsot	1.0	Wheat, rice, peanut and mungbean	Borah *et al.* (2009); Roy *et al.* (2009); Nithya *et al*. (2010)
Lantana camara L.	Verbenaceae	Vermi-compost, mulch	-	Wheat	Borah *et al.* (2009); Nithya *et al.* (2013)
Lencaena glauca Linn.	Legumiosae	Mulch	1-2	Rice	Xuan *et al.* (2005)
Mikania micrantha H.B.K	Astraceae	Vermi-compost		Wheat	Borah *et al.* (2009); Nithya *et al.* (2013)
Morus alba L.	Moraceae	Mulch	2.0	Rice	Hong *et al.* (2004); Khanh *et al.* (2005)
Parthenium hysterophorus L.	Asteraceae	Compost, green manure, vermi-compost	1.0-10.0	Maize, sunflower and rice	Arthanari *et al.* (2009); Aundhekar and Gore *et al*. (2009); Gore *et al.* (2009); Borah *et al.* (2009); Roy *et al.* (2009); Nithya *et al.* (2010); Denesh *et al.* (2010); Devi and Khwairakpam (2021)
Saccharum munja L.	Poaceae	Vermi-compost	1:1-1:3 weed-dung combination	Mung bean	Saha *et al.* (2018)
Tephrosia candida DC.	Fabaecae	Mulch	2.0	Rice	Hong *et al.* (2004); Khanh *et al.* (2005)

production practice. Nevertheless, an acute shortage of conventional organic manures (like animal dung) necessitate exploitation of other sources of organic manures like weed compost and green manuring (Table 1). Studies have shown that integrated application of compost and chemical fertilizer performed better than either sole or combined application of FYM and chemical fertilizer (Sharma *et al.* 2008; Saha *et al.* 2018). There is a possibility to supplement 25–50% nutrients through weed composts (Rajkhowa 2008; Sharma *et al.* 2008) in field crops. Composts prepared from weeds had a higher nutrient level and a lower C to N ratio than compost prepared from crop straw (Mahanta and Jha 2009). Moreover, weed composts performed better in improving soil nutrient status, soil microbial population, nutrients uptake by crop plants, and crop yield (Rajkhowa 2008; Sharma *et al.* 2008; Najar 2017).

Basal application of compost prepared from weeds along with recommended or reduced dose of inorganic NPK has been reported to increase the soil available NPK with considerable nutrient buildup in the soil at the end of the crop season compared to the initial nutrient status of the soil (Arthanari *et al.* 2009; Roy *et al.* 2009). Studies have also revealed that yield attributing characters and seed yields of finger millet, peanut, transplanted/direct-seeded rice, maize and sunflower were either similar or more by combined application of weed compost and chemical fertilizer (Table 1; Arthanari *et al.* 2009; Aundhekar and Gore 2009; Gore *et al.* 2009; Prasad *et al.* 2009; Roy *et al.* 2009). This indicates that the integrated use of chemical fertilizers and weed compost gave better results in respect of crop yield than the sole application of inorganic fertilizers. Use of *Pa. hysterophorus, Ch. odorata* and *Eu. uniflora* compost at 10 t ha^{-1} along with 75 and 100% recommended dose of chemical fertilizer recorded 34–42 and 36–39% higher kernel yield of maize compared with 75 and 100% fertilizer alone, respectively (Denesh *et al.* 2010). Moreover, the residual effect of above stated weed compost also increased the yield of the succeeding sunflower crop. While studying on aerobic rice, Danesh and Prasad (2010) found that integrated application of inorganic fertilizer and weed compost gave similar or more yield than the integrated use of inorganic fertilizer and FYM. According to Pramod *et al.* (2010), the application of the 100% recommended dose of inorganic fertilizer plus *Ch. odorata/Pa. hysterophorus/Eu. uniflora/Eleusine coracana* compost each at 2.6 t ha^{-1} gave maize kernel yield similar to the 100% recommended adose of inorganic fertilizer plus 10 t ha^{-1} FYM. They attributed these results to the higher biomass of microorganisms in the soil and increase in dehydrogenase, and phosphatase activity (Prasad *et al.* 2009), soil EC, organic carbon, total phenolics, microbial respiration and urease (Jiao *et al.* 2021). In short, harvesting weeds for composting is a potential alternative to chemical weed control (Ozores-Hempton 1998). This leads us to conclude that bio-management of weeds as a source of compost is an excellent option to enhance crop yield and improve soil fertility potential.

Weeds as a source of mulch

Crop residues as mulches have always been around as an agricultural tool. In recent years, scientists have increased their focus to conserve resources by adopting conservation agriculture due to the unsustainability of modern agriculture (Farooq *et al.* 2011). To achieve the benefits of conservation agriculture, permanent soil cover using crop mulches is an important attribute. Additionally, retention of permanent mulch on the soil surface is more critical to adopt conservation agriculture in temperate countries where tillage is much reduced (Erenstein 2003). Mulchingat 30% covering of the soil surface decreased soil erosion by 80%, while the increasing percent soil cover resulted in more reduction in soil erosion (Allmaras and Dowdy 1985; Erenstein 2003; Doring *et al.* 2005). Furthermore, mulching has the potential to improve crop growth and yield (Table 1) by inhibiting growth of weeds, minimizing soil evaporation, improving capture and use of rain water, enhancing water infiltration and retention, reducing maximum temperatures in the soil surface layers, and increasing aggregate stability and soil porosity (Ramakrishna *et al.* 2006; Bationo *et al.* 2007; Adeniyan *et al.* 2008). However, in most of the farming systems, availability of crop residues for mulching is a major constraint to adopt conservation agriculture.

Recently, attempts are being made to use weeds as mulch for crops and vegetable production (Table 1). Weeds have been successfully used as an effective source of organic mulches. Plenty of weed biomass is available everywhere that can be used as a good mulching material with an economic advantage over polythene mulch. The research reports have indicated the usefulness of weeds *e.g. La. camara* and *Ei. crassipes* biomass as mulch for increasing maize, rice, wheat, bell paper, okra, potato, tobacco, tomato, green gram and banana yield and quality (NPK and sugar contents) compared with crop organic mulches (Table 1). Furthermore, increase in phosphorus use efficiency, soil organic carbon, available nitrogen content and soil moisture conservation with weed mulch compared to FYM application has been observed (Barman and Varshney 2009).

Mulches have also been used as an alternative to herbicides for effective weed control (Dalzell *et al.* 1987). Mulches were an important method of weed control prior to the development of herbicides (Ozores-Hempton 1998). Suppressive effects of mulches suppress weed growth by causing physical hindrance as well as by releasing phytotoxic compounds (Ozores-Hempton 1998). Thus, it is more practical to use mulches in wide-spaced crops, particularly transplanted crops.

According to Xuan *et al.* (2005), use of weeds as organic mulches for weed management can sometimes control weed growth as effectively as herbicides. For example, *Pa. hysterophorus* mulching at the rate of 5 t ha^{-1} can significantly reduce weed infestation in soybean and enhance soybean production (Siddiqui *et al.* 2018). The mulches of a number of weeds like *Ageratum conyzoides* (L.), *Avena fatua* (L.)., *Bidens pilosa* (L.), *Centaurea maculosa* (Lam.) and *Tephrosia hirta* (L.) could be used to control weeds and for the reduction of herbicides dose (Abbas *et al.* 2017c). The use of weeds as mulches also promoted rice growth and yield, and greatly reduced paddy weed growth at an amount of 2 t ha^{-1} (obtaining over 80% weed control) and increased rice yield by 20% (Hong *et al.* 2004; Khanh *et al.* 2005). Thakur and Dalal (2013) used three herbicides (pendimethalin, paraquat and pyrazosulfuron-ethyl), weed mulches and plastic mulches to control broad- and narrow-leaved weeds in jujube (*Zizyphus mauritiana*) and found the highest weed control efficiency and more buddable plants of jujube with weed mulch and in the weed-free control. Likewise, the potential of *Brachiaria ruziziensis* (Germ. and Evrard.) as a weed mulchat 4–8 t ha^{-1} has been reported by Oliveira *et al.* (2014). The degree of weed control depends on mulch thickness, weed species, and environmental conditions. Weed control usually improves as the thickness of the organic mulch layer increases (Ozores-Hempton 1998; Siddiqui *et al.* 2018). Generally, to suppress weeds most effectively, a 5 to 7 cm thick layer of mulch is needed. Thus, use of weeds as mulch can be a possible sustainable ecofriendly alternative to chemical weed control and in the long run, it will lead to improved soil organic matter contents, soil microflora, reduced soil weed seed bank and sustainable crop production.

Weeds as a source of hay and silage

Weeds always invade agricultural land including crop fields, orchards, road sides and pastures. Hence, it is essential to know the nutritional potential of different weed species before making a management decision concerning weed control. It is often presumed that weeds have low nutritional values and low palatability for livestock (Lewis and Green-Jr 1995). Therefore, costly, environmentally toxic and time consuming methods are mostly practiced to control weeds (Marten and Andersen 1975; Nadeem *et al.* 2017). Some weed species have thorns (for example *Cirsium vulgare* Savi., *Carduus nutans* L., *Lycium ferocissimum* Miers., *Solanum atropurpureum* Schrank., *So. carolinense* and *Tribulus terrestris* L.), whichmay injure the mouth and eyes of animals, while some weeds may reduce the quality and quantity of milk and meat (Lewis and Green-Jr 1995). However, many weeds are nutritionally rich, and have higher palatability and digestibility than common forages (Lewis and Green-Jr 1995; Farooq *et al.* 2021). Therefore, it is important to recognize the nutritional potential of common weeds to make quality hay and silage. Further attention in this domain may help to fulfill the shortage of nutritious food to livestock, especially during forage shortage periods. It will also lead to a positive alternative to reduce the hazards produced during chemical weed control.

Nutritive value of weeds

Previously, weeds were assumed to have a low nutritive value and unpalatable for most of the animal species (Nashiki *et al.* 1984; Brockman 1985; Marten *et al.* 1987), thus the importance of weeds as silage has not received considerable attention. Although a large number of weeds including grasses (*Ec. crus-galli* L., *Bromus tectorum* L., *Hordeum jubatum* L., *Setaria viridis* L. and *Av. fatua*) and broad leaved (*Chenopodium album* L., *Descurainia sophia* L., *Amaranthus retroflexus* L., *Convolvulus arvensis* L., *Am. viridis* and *Rumex crispus* L.) are consumed by animals as fodder in Pakistan, India, Sri Lanka, Bangladesh and several other developing countries (Bakshi *et al.* 2005; Khan *et al.* 2013; Tozer *et al.* 2015). Weeds may also help poor landless farmers who do not have enough land to cultivate fodders for their animals.

Weeds are presently a valuable resource of fodder for many people in Khyber Pakhtunkhwa (Pakistan); about 46% of domestic animals depend on weeds as a source of fodder and just 7% used cultivated fodder (Khan *et al.* 2013). In addition, various weed species including *A. hybridus*, *A. spinosus*, *Cleome gynandra* L., *Cucumis metuliferus* L., *Cu. anguria* and *Corchorus tridens* L., are being consumed as green vegetables for human food, and thus play an important role in the household economy (Maroyi 2013).

Recent studies have explored the suitability of weed species as fodder and their nutritive values for animals (Bakshi *et al.* 2005; Payne 2009; Khan *et al.* 2013; Tozer *et al.* 2015; Farooq *et al.* 2021). The nutritional composition of weeds is an important factor to determine their silage quality. For example, some weeds contain toxic chemicals that make them poisonous for livestock food. Common poisonous weeds found in pastures and fodder crops include *Conium maculatum* L., *Cicuta maculate* L., *Pteridium aquilinum* L., *Triglochin palustris* L., *Equisetum arvense* L., *Phytolacca Americana* L., *Caltha palustris* L. *and Helenium automnale* L. (Cooper and Johnson 1984; Zhao *et al.* 2008). On the other hand, many weed species have the best nutritional compositions for livestock feed. Farooq *et al.* (2021) explored that invasive weed *A. philoxeroides* contain nutrients comparable to common fodder crops *e.g.*, iron (34.4–64.5 mg kg1), zinc (15.1–29.8%), manganese (2.3–3.6%), acid detergent fiber (13.0–17.9%), neutral detergent fiber (23.3–38.9%) and crude protein contents (10.2–14.2%) were ranging 13.0–17.9, 23.3–38.9 and 10.2–14.2%, respectively. Khan *et al.* (2013) determined the nutritional worth of sixteen common weeds for their use as livestock consumption; most of the weed species were rich in calcium, zinc, copper, iron, sodium and magnesium. They further concluded that broadleaved weeds contained high mineral and protein concentrations as compared to grassy weeds, while more fiber was observed in grassy weeds. Bakshi *et al.* (2005) reported that grassy weeds possess good quantity of different nutrient worth estimating parameters including organic matter (88–93.5%), crude protein (4.7 to 8.3%), neutral detergent fiber (76.9–87.8%) and acid detergent lignin (6.75–9.87%). Most of the weeds were rich in calcium and magnesium, and had small rumen fill values, showing their worth for good dry matter intake. Gutierrez *et al.* (2008) investigated the nutritional composition of 14 local weed species and concluded that mineral concentrations of weeds were at the safe level for livestock use. Additionally, most of the weeds possess the recommended range of crude fiber and protein for excellent growth of livestock. Study on influence of *Xanthium strumarium* infestation on nutritional value of tall fescue (*Festuca arundinacea*) pastures revealed that increasing densities of the weed did not cause any decrease in nutritive values of total biomass (Rosenbaum *et al*. 2011).

The difference between the nutritive worth of fresh forage samples and silage needs to be determined for weed silage. Analysis of fresh samples may vary with the nutritive contents in hay or silage (Grabber 2009). Mineral composition calcium-to-phosphorus ratio (Ca: P) is considered as an important factor to determine the quality of silage. Most of the weed species have Ca:P ratio under the safe range for livestock production (Marten *et al.* 1987). Only few weed species, (including *Abutilon theophrasti* and *Ambrosia trifida* L.) have a high Ca: P ratio that could cause a problem only if they used alone for hay production, however, it is very rarely happened in pastures and other hay production systems due diverse weed-species composition (Marten and Anderson 1975). These studies suggest that many weed species have significant nutritive worth for livestock feed. Therefore, these weeds can be used as a source of silage making. Production of silage from weed species can contribute well to provide nutrient rich and economically affordable feed to animals in winter. Since no weed species have been used for silage production, further research on this aspect is required to investigate the quality, shelf-life and potential of weed made silage for livestock use.

In vitro dry matter digestibility of weeds

In vitro dry matter digestibility (IVDMD) of forage represents the degree to which plant tissue is observed in the digestive track of animals and is an important parameter to check their potential as silage. Many weeds have more IVDMD as compared to some cultivated forages (Abaye *et al.* 2009). Marten and Anderson (1975) compared the nutritive value and palatability of different annual weeds with alfalfa and reported that *Am. retroflexus* and *Ambrosia artemisiifolia* had more IVDMD as compared to alfalfa, whereas *Che. album*, *S. glauca* and *Ec. crus-galli* showed almost similar IVDMD to alfalfa. Studies also showed that *Am. artemisiifolia*, *Ab. theophrasti*, *Am. retroflexus*, and *Ec. crus-galli* had more palatability and digestibility than cultivated oats (*Av. sativa*) grown for forage purposes (Marten and Anderson 1975). Later on, Marten *et al.* (1987) comparatively studied the forage nutrition and palatability of ten different weeds at their vegetative and bud stages with alfalfa and found that most of the annual and perennial weeds including *Taraxacum officinale* L., *Silene alba* L., *Sonchus arvensis* L., *Helianthus tuberosus* L., *Berteroa incana* L. and *Ci. arvense* had similar or higher IVDMD compared with alfalfa.

Palatability and digestibility of some weeds decreased very quickly as compared to forage crops as the weeds mature (Bosworth *et al.* 1985). But it is not true for all weeds, for example, winter annual *Lamium amplexicaule* L. and *Geranium carolinianum* L. retained high digestibility even at maturity. Bosworth *et al.* (1980) studied the digestibility of 13 herbaceous weeds and five grass weeds and compared these with two common forage crops Bermuda grass (*Cynodon dactylon* L.) and pearl millet (*Pennisetum glaucum* L.). All weed species showed more crude protein and IVDMD as compared to forage crops. Additionally, *Cu. anguria*, *Am. retroflexus*, *Senna obtusifolia* L. and *Ipomoea* sp. retained constant IVDMD at different growth stages (Bosworth *et al.* 1980).

Previous information on weed hay or silage, and its nutritive quality and self-life are limited. However, research on the quality of forage hay containing weeds revealed that the weed concentration influences the quality of hay, depending upon the type of weeds (Dutt *et al.* 1982). Weeds of crops may not necessarily be weeds for forage, silage or hay formation. For example, *Lolium rigidum* Gaud. is considered as a problematic weed in cereal crops, but, it has a good nutritive value and considered good for silage or hay making (Pinos-Rodríguez *et al.* 2002).

About 40% area of the earth is covered with garasslands and almost 50% of this area is currently used for crop production (Lal *et al.* 2018). Grasslands are mostly covered by weeds, which are very important for carbon sequestration and sustainable hay production (Lal *et al.* 2018). Keeping in view these facts, it is crucial to determine the potential of individual weed species for silage production and their nutritive worth for livestock. Further studies in this regard will help to understand how grassland weed species composition influences the hay and silage quality. Additionally, it would provide an alternative way to manage weeds in field crops by using them for silage making. It will enhance the farmers' income and reduce the use of herbicides to provide healthy foods with less environmental damage.

Weeds as a source of bio-herbicides

Herbicides with new modes of actions are badly needed due to fast increasing resistance against all major herbicide groups. In addition, weed management in organic production systems is a great challenge due to lack of natural herbicides. Various natural herbicidal compounds have been identified from different microbes and crop species (Duke *et al.* 2000; Czarnota *et al.* 2001). These natural phytotoxins offer a great opportunity to be directly used as natural herbicides and to develop novel herbicide mode of actions (Dayan and Duke 2014). In this regard, several weed species are now getting importance as a potential weed-controlling agent because of having various phytotoxic compounds. These phytotoxic compounds are able to inhibit the germination and growth of many other weed species, even those which gain resistance to herbicides. Different weed species including *Che. album*, *Medicago denticulata* L., *Melilotus indica* L., *Co. arvensis*, *Vicia hirsute* L., *Lathyrus aphaca* L. and *R. acetosella* showed strong herbicidal potential to control *Phalaris minor* Retz. (Om *et al.* 2002). *Acroptilon repens* L., a commonly found weed in the western US, showed herbicidal potential against *E. crusgalli, Agropyron smithii* Rydb and *B. marginatus* Steud. (Stevens 1986). Aqueous extract of different plant parts of *Croton bonplandianum* Baill., exhibited herbicidal potential against weeds including *M. alba* L., *Vi. sativa* and *M. hispida* Gaert. (Sisodia and Siddique 2010). However, rare studies are available on identification and extraction of herbicidal compounds from weed species.

D'Abrosca *et al.* (2001) identified 24 different phytotoxic compounds in *Sambucus nigra* L. belonging to various groups including lignans, cyanogenins, phenolic glycosides and flavonoids. These phytotoxic compounds showed strong inhibitory effects on germination and growth of lettuce (*Lactuca sativa* L.), onion (*Allium cepa* L.) and radish (*Raphanus sativus* L.) (D'Abrosca *et al.* 2001). Honey weed (*Leonurus sibiricus* L.) contain various phytotoxic compounds that showed an inhibitory effect on rice, wheat and mustard (Mandal 2001). Aqueous extract of *Conyza canadensis* L. showed a strong inhibitory effect on various crops due to the presence of different phenolics, including gallic acid, syringice acid, cathecol and vanillic acid (Ameena and Sansamma 2002). Sasikumar *et al.* (2002) stated that the strong inhibitory effect of different plant parts of *Pa. hysterophorus* on the germination and growth of various crops was due to the presence of phenolic acids identified in this weed. Similarly, *Che. ambrosioides* and *Ec. crus-galli* also contain various phytotoxic compounds that were found to inhibit the germination and growth of different crop species (Hegazy and Farrag 2007; Khanh *et al.* 2008). Zohaib *et al.* (2016) reviewed more than 30 weed species containing phytotoxic compounds that showed strong inhibition against various crops and weeds, the phytotoxic potential of these weeds can be explored to manage weeds. The most commonly found phytotoxic compounds in weeds were alkaloids, fatty acids, phenolics, terpenoids, indols, lignans, cyanogenins, flavonoids and coumarins (Zohaib *et al.* 2016). Furthermore, allelopathic compounds released from aquatic weeds showed more phytotoxic response against various terrestrial weeds and crop plants (Abbas *et al.* 2017a), because plants of a certain ecosystem might be well adapted to the allelochemicals compared to the ones of any other ecosystem (Reigosa *et al.* 1999; Abbas *et al.* 2017a). Thus, phytotoxic compounds released from aquatic weeds can be identified and used as potential bio-herbicides. In addition, these phytotoxins may also promote the growth of crop plants at low concentrations (Abbas *et al.* 2017b). Therefore, optimizing the time of application and selectivity of various phytotoxins, which can work as bio-herbicides for weeds, would help to control weeds with enhanced crop growth. In crux, the use of chemical herbicides is not a sustainable option for crop production due to the fast-increasing herbicide resistance problem in weeds and environmental hazards of herbicides. Therefore, the use of weeds to make bio-herbicidescan bean environment-friendly option to control weeds in crops for sustainable crop production.

Weeds as a source of biofuel

Weeds have great potential to be used as a biofuel source (Premjet *et al.* 2012; Ali *et al.* 2020; Kataki and Kataki 2022) for energy generation by employing suitable conservation technology. Weed biomass for energy generation can have multiple socio-economic and environmental benefits along with having local and global perspectives (Kataki and Kataki 2022). Weed biomass contains cellulosic or lingo-cellulosic that is important from the energy conservation (Kataki 2009; Premjet *et al.* 2012) and can be feedstocks for anaerobic digestion, briquetting/compaction and prolysis/carbonization for solid, liquid and gaseous fuels. Azwar *et al*. (2022), revealed that aquatic weeds have high contents of lignocellulose, carbohydrate, protein and lipids, and thermochemical techniques can be potentially used for biofuel production from aquatic weeds. Deoxy-liquefaction was applied for thermo-chemical conversion of some aquatic weeds for energy generation (Azwar *et al.* 2022). Various grassy weeds (C_3 and C_4) were evaluated for their potential as biofuel production (Azwar *et al.* 2022), among others two C_3 weed species *Arundo donax* L. and *P. arundinacea* were more useful as biofuel species. Furthermore, *Ip. carnea, Eupatorium adenophorum* Spreng., *Ei. crassipes, He. tuberosus*, *Miscanthus sinensis* Anderss. and *Phragimites australis* Cav. have shown potential to produce bioenergy (Jiang and Zhang 2003; Suganeshwari and Ramani 2014; Vaicekonyte *et al.* 2014). Weeds including *Ar. donax, S. spontaneum, Mi. micrantha, La. camara*, *E. crasspies* and *C. squalida* L. can be used for the production of alcoholic biofuels (Borah *et al.* 2016; Ogunjobi *et al.* 2016).

Mixing (10% by weight) of *Pa. hysterophorus* with cattle manure as a substrate produced 60–70% methane (CH_4) (Gunaseelan 1987). Furthermore, *Pa. hysterophorus* biomass alone has potential to produce 75% CH_4 (Gunaseelan and Lakshmanperumalsamy 1990). Carefulanaerobic digestion of different weeds including *Ei. crassipes*, *Cannabis sativa* L., *Croton sparsiflorus* and *Pa. hysterophorus* showed significant production of biogas that varied from 90 to 100 L/kg (Thakur and Singh 2003). Studies have revealed that addition of weed biomass to cow dung boosted the biogas production, and residues can be used as an effective source of manure (Kannan *et al.* 2003; Gitanjali *et al.* 2009), because degradation of phytotoxic allelochemicals that may inhibit microbe and plant growth has been reported during biogas production process (Gunaseelan 1998).

The introduction of weed species as a source of biofuel is a major challenge until profits clearly out weigh possible damages because weeds may become invasive and may cause more harm to crops (Ali *et al.* 2020). Introducing weed species for the source of biofuel may be safe, but safety should need to be analyzed by agronomic and environmental aspects. However, controlling weeds in crops as source of biofuel production is safe and very economical for farmers. Further research is required to evaluate the potential of other weeds as a source of biofuel.

Weeds as biosorbent

Weeds including *Cyanthilium cinereum* and *Paspalum maritimum* were explored as potential weed for the biosorption of methylene blue dye in effluents (Silva *et al.* 2019). Further, another weed *Salvinia minima* also explored as effective natural absorbent for removal of dye and heavy metals from wastewater (Sachan *et al.* 2023). *Ageratina adenophora*, a weed plant also evaluated as potential and cheap biosorbent for removal of Cu from aqueous solution (Fan *et al.* 2022). Two weed species including *Lotus corniculatus* and *Am. viridis* have been identified as natural absorbents for removal of heavy metals (cadmium, chromium, lead and zinc) from water (Moussa *et al.* 2022). Further, various aquatic weeds proved as an excellent absorber to absorb heavy metals and pharmaceutical pollutants from agricultural, domestic and industrial wastewater (Mustafa and Hayder 2021). Recent studies showed an encouraging trend regarding biosorbent potential of weeds. Weed-based biosorbent have great potential to effectively remove heavy metals from wastewater. Further, with regeneration of biosorbents these can be reused even up to 10 times. Cost analysis confirmed that weed-based biosorbents are economically inexpensive than old-style adsorbents for example activated carbon (Syeda *et al.* 2022).

Weeds for phytoextraction

Phytoextraction is ecofriendly, cost-effective and fast emerging technique to remove heavy metals from soil. Weeds showed promising potential for phytoextraction, effectively removing contaminates from soil (Pathak and

Bhattacharya 2021). Various weed species including *Ip. carnea, Jatropha curcas*, *Trianthema portulacastrum*, *Cy. dactylon, Typha angustifolia*, *Phyllanthus reticulatus*, *E. colonum*, *Vetiveria nemoralis*, *Am. viridis* and *El. indica* showed great potential to remove different heavy metals including Cd, Cr, Pb and Hg from soil (Pathak and Bhattacharya 2021). A common weed, *Calotropis procera*, exhibited strong potential to grow in contaminated soil and remove arsenic (As) from As contaminated soil (Singh and Fulzele 2021). In a long term field study, *Celosia argentea* successfully removed cadmium (Cd) form the Cd contaminated soil (Yu *et al.* 2020). Removal of heavy metals is done by absorption in undergrounds and above ground parts. Each weed species has specific physiological and molecular interaction with heavy metals; thus, uptake potential is influenced by plant genotypes and its environment. Hence, it is crucial to understand heavy metal tolerance mechanisms in weed plants and identify weed plants which are more tolerant to heavy metal stress and perform well under changing climate (especially high temperature and drought stress).

Other uses

Biochar preparation: Weeds can be used for biochar production, for instance, biochar produced by pyrolysis of *Pa. hysterophorus* was effective to improve soil quality and increase maize yield (Kumar *et al.* 2013). Furthermore, the addition of this biochar to soil enhanced microbial biomass carbon, improved catalase and dehydrogenase functions and reduced hydrolytic enzymes activities (Kumar *et al.* 2013). Phytotoxic compounds present in *Parthenium* (Patel 2011) were degraded during the process of biochar production at high temperatures. Thus, addition of a large quantity of biochar showed no phytotoxic effect on soil or crop. Thus the use of weeds, even those having a strong allelopathic effect, is safe and effective for biochar preparation.

Dye degradation: Textile dyes are expensive and cause strong environmental degradation effects, especially when disposed untreated. They damage different microflora present in soil and water bodies that result in ecological imbalance. Exploiting the degradation potential of plant enzymes is an effective and environmentally safe alternative to inorganic toxic textile dyes. Weeds can be used for dye degradation, for example, phenol oxidase extraction from young leaves of *Pa. hysterophorus* was effective to remove various dyes (Shinde *et al.* 2012). Higher concentrations of the extract showed quick results to remove yellow and brown dyes. Additionally, this extract showed no toxic effect on treated water (Shinde *et al.* 2012). Thus, extraction of dyes degradation enzymes from various weeds can help to save cost and environmental damage.

Paper making and cellulose production: Various weed species are a rich source of lingo cellulosic biomass. Premjet *et al.* (2012) determined the concentration of lignin, hemicelluloses and cellulose of 77 weed species; various weed species contained up to 20% lignin, 32% hemicelluloses and 56% cellulose. These lingo cellulosic concentrations are more than those in oat, barley, maize and rye straw (Chandel and Singh 2011). Thus, weeds can be used as low a cost and easily available raw material for production of various qualities of papers with an acceptable strength and suitable quality for several commercial uses (Ji *et al.* 2012). Bhodiwal *et al.* (2024) revealed that *La. camara* has good physical streng that different NaOH concentrations proving that *Lantana* fiber can be successfully used for paper making. Chemical characteristics of three weed species including *Merremia peltata* (L.) Merr., *Am. viridis,* and *Andropogon saccharoides* var. *erianthoides* Hack. were analyzed for their potential for paper making, outcomes revealed that holocellulose and lignin contents found in these weeds were comparable with holocellulose and lignin contents of wooden trees (Neelagar *et al*. 2018). Outcomes exhibited the great potential of these weed species for raw material in pulp and paper industries.

Lignocellulosic substrates from weeds can be used for production of water soluble α-cellulose (WSC) (Swaminathan *et al.* 1990). WSC can be further modified by esterification or etherification to obtain derivatives of WSC like carboxymethyl, cyanoethyl, hydroxyl methyl, ethyl, methyl, hydroxyphenyl methyl, and carboxymethyl hydroxyethyl cellulose. These celluloses have many applicable uses as additives in chemicals used in various industries. Different weed species, for example, *Achyranthes aspera* L., *Leucaena leucocephala* Lam., *Sida acuta* Burm. and *Pa. hysterophorus* can be considered as a good candidate for the production of WSC (Bhodiwal *et al*. 2024).

Corrosion inhibition: Studies are available on the other direct uses of weeds like corrosion inhibition (Ji *et al.* 2012). For example, the above ground plant parts extract of *Cnicus benedictus* can be potentially used as natural steel corrosion inhibitor in HCL media with excellent efficacy (92.45%) at 1000 mg. kg^{-1} (Thakur *et al.* 2022). Recently, *Colocasia esculenta* extract has been examined as good corrosion inhibitor with efficacy of more than 93%, increasing extract concentration from 100 to 500 mg/L in acid solution caused increase in efficacy (Singh *et al.* 2023).

Conclusion

Due to issues regarding the use of herbicides including fast increasing herbicides resistance, herbicide hormesis in weeds, environmental and health hazards, it is essential to find efficient alternatives to chemical weed control. The bio-management of weeds through their utilization as value added products is a good option for sustainable weed management and to enhance the farmers' income. Weeds can be used to make various value-added products including medicines, compost, mulches, hay and silage, bioherbicides, and biofuel that might enhance the economic return of farmers. The great potential of weeds to make value-added products can be utilized by farmers, scientists, and industrialists to build soil with the organic source, control weeds by natural mulches and herbicides, safe medicines to ensurehuman and animal health, natural feed for livestock and environmentally safe source of fuel. Various weed species showed great potential for dye degradation, paper making and cellulose production, corrosion inhibition, biosorbent and phytoextraction. In addition, this will save drainage of money for purchasing inorganic fertilizers and herbicides. Bio-management of weeds as value added products may provide a miracle in weed control technology. However, it is advised that weeds should be removed from the cropped and non-cropped areas timely for use as value added products to reduce the weed seed dispersal and harmful effects on crop plants. It will reduce weed intensity at agricultural farms and soil productivity and profit of the farmers will be enhanced on a sustainable basis. Continuous efforts at agricultural universities and research institutes are needed in different agroecological zones for developing compost making technologies for weeds with higher biomass production particularly in the developing countries to lessen the use of off-farm fertilizer resources. Farmers' group meeting, training, and demonstration trials can be organized to spread this technology and build-up farmers' confidence.

Acknowledgement

The authors would like to acknowledge support from University of Sargodha.

Author Contributions

TA, conceptualization, writing—original draft preparation, writing—review and editing; MAN, writing—review and editing, supervision, resources; NRB, conceptualization, writing—review and editing; AM, writing—review and editing; MK, writing—review and editing; MKM, writing—review and editing; MTAK, data curation; NF, writing—review and editing, project administration, data curation. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

All authors declare no conflict of interest.

Data Availability

Data presented in this study will be available on a fair request to the corresponding author.

Ethics Approval

Not applicable to this paper.

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