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Weed management in cotton (*Gossypium hirsutum* L.) through weed-crop competition: A review

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A B S T R A C T

The agriculture sector is embracing energy efficient conservation systems and technological innovations to meet the ever increasing demand for food, fibre, and fuel in tune with the rapidly increasing human population. The genetic modification of plants is one of the technological innovations that is adopted rapidly across the world. In cotton, many major producing countries have adopted herbicide-tolerant genetically modified crops. Over-reliance on herbicides for weed management in both genetically modified and conventional systems has led to the rapid evolution of herbicide-resistant weeds. Poor weed management can cause up to 90% yield loss in cotton. Undoubtedly, integration of non-chemical methods and diversifying weed control options would ensure the sustainability of available weed management options, including herbicides. Increasing crop competitiveness is one of the approaches that could be integrated with the current weed management systems. Choosing cultivars with early vigour, use of narrow row planting, orienting crop rows with regard to sunlight, and adjusting planting density are some of the approaches that could enhance the competitiveness of crops over weeds. Review of the available literature on cotton indicates weed suppressive benefits by enhancing crop competitiveness through increasing planting density and narrow row spacing. Early canopy closure in narrow row spaced systems would suppress many problem weeds. In addition, herbicide efficacy may be increased due to competition offered by a dense crop stand, which may reduce herbicide selection pressure on weeds. However, the use of narrow row spacing is still in an infant stage in many cotton-growing countries and the success may depend on the environment, soil type, and resource availability. This review analyses and reports the potential benefits of increasing crop competition as a weed management option and also highlights research to be undertaken to ensure the adoption of different strategies on a much wider scale.

1. Introduction

Cotton (*Gossypium hirsutum* L.) is the most preferred natural fibre and contributes to a one-third of the total fibre traded on a global scale (NCC, 2015). China, India, USA, Pakistan, Brazil, Uzbekistan, and Australia are the major producers of cotton (NCC, 2015). Emerging weeds in cotton production zones and their management is a major crop production challenge across the world (Berger et al., 2015; Culpepper, 2006; Werth et al., 2006; Jabran, 2016). Poor weed management in cotton can lead to a significant yield reduction; depending on weed management, yield reductions can range from 10 to 90% (Dogan et al., 2015; Morgan et al., 2001; Oerke, 2006; Robinson, 1976). Rapidly emerging herbicide-resistant weeds further adds to the complexity of cotton weed management (Webster and Sosnoskie, 2010; Werth et al., 2011). A major change that occurred in the cotton farming is the rapid adoption of genetically modified herbicide-tolerant cultivars (GM cultivars), of which glyphosate-tolerant cotton accounts a major proportion (ISAAA, 2015). Herbicide-tolerant cultivars offer myriad of benefits, such as flexibility and efficiency in weed management, and better

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economic returns; however, over-reliance on a single herbicide without diversity has led to the emergence of many problem weeds in cotton growing zones (Norsworthy et al., 2007; Werth et al., 2013). Many weeds rapidly evolved glyphosate resistance due to the intense selection pressure from glyphosate. For example, in the USA, many populations of *Amaranthus palmeri* S. Wats. have evolved resistance to glyphosate (Sosnoskie and Culpepper, 2014). A study indicated that continuous use of glyphosate led to the shift of weeds (Johnson et al., 2009). In this study, the dominant weeds *Cirsium vulgare* (L.) Scop., *Setaria* sp., and *Abutilon theophrasti* Medik. were shifted to *Sorghum halepense* (L.) Pers., *Amaranthus* sp., *Conyza canadensis* (L.) Cronquist, and *Chenopodium album* (L.) Cheal. over a period of 16 years from 1990 to 2005, in the glyphosate-tolerant corn (*Zea mays* L.) system of the eastern corn belt of the USA (Johnson et al., 2009). In Australia, a survey conducted across the cotton growing zones in 2011 indicated an increase in the prevalence of *Conyza bonariensis* (L.) Cronquist., *Sonchus oleraceus* L., *Chloris virgata* Sw., and volunteer cotton (glyphosate-tolerant) compared to the previous survey of 2008 (Werth et al., 2013). Although the GM technology was highly successful in the initial years of introduction, the economic advantage and easiness in weed management decreased rapidly due to the rapid evolution of herbicide-resistant weeds (Sosnoskie and Culpepper, 2014).

Evolution of herbicide resistance, shifts in weed populations, environmental pollution, and high weed management costs are some of the consequences of a weed management program that is predominantly based on herbicides (Culpepper, 2006; Myers et al., 2016; Owen et al., 2015). Therefore, it is always advisable to integrate available non-chemical methods to sustain the efficacy of different weed management options and herbicide resources (Norsworthy et al., 2012; Owen et al., 2015). Use of weed-competitive cultivars, use of narrow row planting, adjusting planting density, and adjusting row orientation are some of the options that could enhance competitiveness of crops over weeds (Borger et al., 2016; Dogan et al., 2015; Norsworthy et al., 2012; Owen et al., 2015). Various methods were researched and adopted in the cotton growing regions across the world (Dogan et al., 2015). However, the success rate of these methods depends on the multitude of factors, such as soil types, climate, available water resources, cultivars, prevailing weeds and agronomic management. This article reviews the available literature on weed management in cotton by enhancing crop competition through various options, and reports the potential benefits of increasing crop competition. Unlike many other crops, limited research has been carried out on various approaches that enhance crop competitiveness in cotton, and these approaches are adopted at a limited scale across the cotton growing zones around the world. Therefore, this review emphasises on the research to be undertaken to ensure the adoption of various options to enhance crop competition, and increase the adoption on a much wider scale.

2. Weed flora and their competitiveness in cotton

Cotton is a perennial plant and can completely cover the land area with canopy, although the time taken for this can vary depending on the environment, management, plant density, and row spacing (Bukun, 2004; Papamichail et al., 2002; Wright et al., 2000). Cotton is slow in initial establishment (Ortiz and Bourland, 1999), and weeds, if uncontrolled during the initial phase, may result in yield penalty (Wilson et al., 2007). In general, 9–11 weeks of a weed-free period is required in cotton planted at a row spacing of 1 m (standard rows) (Bukun, 2004; Papamichail et al., 2002).

There is a commonality in weed flora across the world, possibly because of similarity in agronomic management and climatic requirements (Table 1). Weeds may vary in their yield reduction potential. In a study conducted in Oklahama, *S. halepense* reduced cotton yield significantly (Wood et al., 2002). There was a lint yield reduction of 5.5% for every one plant per 15 m row (Wood et al., 2002). *Eleusine indica* (L.) Gaertn. at a density of 4 plants m^{-1} row reduced cotton yields by 20–27% (Ma et al., 2015a). Competition studies indicated that certain weed species are highly competitive in cotton. For example, *Xanthium pensylvanicum* Wallr. was found to be more competitive than *Amaranthus retroflexus* L. at two locations in Alabama (Buchanan and Burns, 1971). In another study, *Cassia obtusifolia* L. Casob was more competitive than *A. retroflexus* and *A. hybridus* (Street et al., 1985). One plant of both *Amaranthus* species and *C. obtusifolia* per 7.5 m row reduced seed cotton yield by 9%. In another study, *C. obtusifolia* did not reduce yield in cotton per 3 m row, whereas 5–7% yield loss was observed when *Anoda cristata* L. Schltdl., *Xanthium strumarium* L. Xanst., *Digitaria sanguinalis* (L.) Scop. *Datura stramonium* (L.) Datst., *C. album*, *Amaranthus retroflexus*, and *Ambrosia artemisiifolia* (L.) Ambel. were present at the same density (Byrd and Coble, 1991).

Some weeds can be competitive throughout the crop growing phases, although certain weeds are competitive at the initial crop growing phases. For example, *Echinochloa crus-galli* (L.) Beauv. is highly competitive at the beginning of the cropping season, and a critical weed-free period of 9 weeks after planting is required to avoid yield loss (Keeley and Thullen, 1991). However, weeds like *A. palmeri* can be detrimental even at later stages of crop growth, as substantial seed production is possible even under competitive environments (Ward et al., 2013). *A. palmeri* can significantly shade cotton and prevent it from reaching its full yield potential (Morgan et al., 2001). Competitive interference of *A. palmeri* indicated that 10 plants per 9.1 m row resulted in a 45% reduction in canopy volume at 10 weeks after planting and reduced cotton biomass to 50% by 8 weeks after planting (Morgan et al., 2001). Similarly, *A. hybridus* can grow taller than cotton and can reach up to 3 m thereby, shade the crop plants (Ma et al., 2015b). This weed at a density of 0.3 plants per m of row could cause a yield reduction of around 50% (Ma et al., 2015b). To further enhance the problems, over-reliance on glyphosate for weed management is favouring many weeds to rapidly evolve resistance to this herbicide (Flessner et al., 2015; Webster and Grey, 2015). There are weeds that are tolerant to glyphosate and repeated selection favoured many such weeds (Webster and Sosnoskie, 2010; Werth et al., 2013). *Commelina benghalensis* L. is a weed that is difficult to control with glyphosate and becoming predominant in the cotton growing zones of the USA (Webster et al., 2005). Similarly, *C. bonariensis* is becoming prominent in the Australian cotton growing zones and is hard to control with glyphosate (Werth et al., 2011). In the US cotton growing regions, *Ipomoea* spp. and *Amaranthus* spp. were evolved as problematic weeds after the introduction of glyphosate-tolerant cotton (Kruger et al., 2009).

3. Weed competitive cultivars

Crop cultivars differ in their competitive ability to supress weeds (Mahajan and Chauhan, 2011, 2013; Eslami, 2015). Integration of competitive cultivars in cropping systems would reduce herbicide usage and the overall weed management costs. In general, weed-competitiveness of cultivars is correlated with plant height, seedling vigour, early canopy closure, leaf orientation, leaf area development, and branching and tillering pattern (Eslami, 2015). During the growth process, cotton plants will branch and expand their canopy leading to complete canopy closure (Jost and Cothren, 2001). Once the canopy is closed, there would be less light penetration into the inter-row spaces and weeds will not be able to compete with cotton as early in the crop establishment period (Jost

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Table 1
Major weeds reported in cotton in different countries.

Scientific name	Country with reported presence	Reference
Alternanthera tenella. Colla.	Brazil	Silva et al., 2009
Amaranthus palmeri S. Wats.	USA	Kruger et al., 2009; Prince et al., 2012; Riar et al., 2013a
Amaranthus retroflexus L.	China and Greece	Economou et al., 2005; Zhang, 2003
Amaranthus rudis Sauer.	USA	Kruger et al., 2009; Prince et al., 2012; Riar et al., 2013a
Amaranthus viridis L.	Brazil	Silva et al., 2009
Cenchrus echnatus L.	Brazil	Silva et al., 2009
Chenopodium album (L.) Cheal.	China and Greece	Economou et al., 2005; Zhang, 2003
Chloris virgata Sw.	Brazil	Silva et al., 2009
Cirsium vulgare (L.) Scop.	Greece	Economou et al., 2005
Convolvulus arvensis L.	Pakistan	Memon et al., 2014; Rajput et al., 2008
Commelina benghalensis L.	Brazil and USA	Kruger et al., 2009; Prince et al., 2012; Riar et al., 2013a, Silva et al., 2009; Werth et al., 2011
Conyza bonariensis (L.) Cronquist.	Australia and Pakistan	Walker et al., 2005; Memon et al., 2014; Rajput et al., 2008; Werth et al., 2011
Conyza canadensis (L.) Cronquist.	USA	Kruger et al., 2009; Prince et al., 2012; Riar et al., 2013a
Cucumis anguria L.	Brazil	Silva et al., 2009
Cynadon dactylon (L.) Pers.	China, Greece and USA	Economou et al., 2005; Kruger et al., 2009; Prince et al., 2012; Riar et al., 2013a; Zhang, 2003;
Cyperus esculentus L.	USA	Kruger et al., 2009; Prince et al., 2012; Riar et al., 2013a
Cyperus rotundus L.	Australia, China, Greece and India,	Economou et al., 2005; Hiremath et al., 2013; Prabhu et al., 2012; Werth et al., 2011; Zhang, 2003
Digera arvensis Forsk.	India	Hiremath et al., 2013; Prabhu et al., 2012
Digitaria sanguinalis (L.) Scop.	China and USA	Kruger et al., 2009; Prince et al., 2012; Riar et al., 2013a; Zhang, 2003
Eclipta prostrata L.	Pakistan	Memon et al., 2014; Rajput et al., 2008
Echinochloa crus-galli (L.) Beauv.	USA	Kruger et al., 2009; Prince et al., 2012; Riar et al., 2013a
Echinochloa spp.	Australia, China and India	Walker et al., 2005; Zhang, 2003; Hiremath et al., 2013; Prabhu et al., 2012; Werth et al., 2011
Eleusine indica (L.) Gaertn.	Australia and China	Werth et al., 2011; Zhang, 2003
Fallopia convolvulus (L.) A. Love.	Australia	Walker et al., 2005; Werth et al., 2011
Hibiscus trionum L.	Australia	Walker et al., 2005; Werth et al., 2011
Ipomoea purpurea (L.) Roth.	USA	Kruger et al., 2009; Prince et al., 2012; Riar et al., 2013a
Lamium amplexicaule L.	Australia and USA	Kruger et al., 2009; Prince et al., 2012; Riar et al., 2013a; Werth et al., 2011
Lolium perenne L. ssp	USA	Kruger et al., 2009; Prince et al., 2012; Riar et al., 2013a
Leptochloa chinesis (L.) Nees.	China	Zhang, 2003
Polygonum aviculare L.	Australia and China	Werth et al., 2011; Zhang, 2003
Setaria viridis (L.) P.Beauv.	China	Zhang, 2003
Senna obtusifolia L.	USA	Kruger et al., 2009; Prince et al., 2012; Riar et al., 2013a
Sida spinosa L.	USA	Kruger et al., 2009; Prince et al., 2012; Riar et al., 2013a
Solanum nigrum L.	Australia and Greece	Economou et al., 2005; Werth et al., 2011
Sorghum halepense (L.) Pers.	Greece	Economou et al., 2005
Sonchus oleraceous L.	Australia	Walker et al., 2005; Werth et al., 2011
Trianthema portulacastrum Linn.	Australia India and Pakistan	Hiremath et al., 2013; Memon et al., 2014; Prabhu et al., 2012; Rajput et al., 2008; Werth et al., 2011
Tribulus terrestris L.	Australia and Greece	Economou et al., 2005; Werth et al., 2011
Urochloa panicoides P. Beauv.	Australia	Walker et al., 2005; Werth et al., 2011
Xanthium strumarium (L.) Xanst.	Greece	Economou et al., 2005
Xanthium spinosum L.	Greece	Economou et al., 2005

and Cothren, 2001). However, as cotton establishes slowly and less competitive when grown in 1 m row spacing (Ortiz and Bourland, 1999), weed competition at an early phase could significantly reduce plant growth and yield (Papamichail et al., 2002). Therefore, from a weed management point of view, cultivars with enhanced seedling vigour would be highly desirable to suppress weeds, as that would ensure weed suppression in the initial crop growing phases (Bertholdsson, 2005; Liu et al., 2015). The commercial cultivars in the USA were compared with breeding lines of Arkansas cotton breeding programme for their seedling vigour (Liu et al., 2015), and found many breeding lines were superior to many commercial lines regarding seedling vigour. The early vigour characteristics were genetically controlled and correlated to seed weight and cotyledon area (Liu et al., 2015). The results of this study are encouraging as there are breeding lines available that could be employed to enhance seedling vigour. In the USA, cotton cultivars AM1511B2RF, NG2051 B2RF, CG3156B2RF, CG3787B2RF, CG3787B2RF, PHY499WRF, DP1646B2XF, DP1612 B2XF are with increased seedling vigour as per the manufactures guidelines (DFA, 2016). In Australia, Sicot 43BRF, Siokra V-18BRF and Siokra 24BRF are the commercial cultivars with high seedling vigour (CSD, 2016). When compared, the Indian cotton cultivar H1226 was superior compared to H1117, and H098 was intermediate in seedling vigour (Madhu et al., 2014). In Iran, new commercial cultivars were compared with old cultivars for their ability to compete with *X. strumarium* (Rezakhanlou et al., 2013). The study indicates less weed-competitiveness for commercial lines compared to the old cultivars. Cultivars Syland and Sindoz yielded high even under competition with *X. strumarium*. Cultivars Mehr and Ariya were the least competitive cultivars. The modern cultivars, although superior in yield had low weed suppressive abilities due to short height, reduced vigour, and low light interception (Rezakhanlou et al., 2013). In Mississippi, when cotton cultivars were compared, Deltapine 16 competed better with *A. cristata* compared to DES 21326-04 and Stoneville 213 (Chandler and Meredith, 1983). The current analysis indicates that not many studies were carried out on how best the commercially available cultivars compete with emerging weeds in the cotton producing zones. Breeding approaches should consider competitiveness (ability to quickly achieve row closure) together with other important breeding characteristics such as compact plant architecture and water use efficiency.

4. Increasing plant density and reduced row spacing

Increasing plant density is a non-chemical tactic that can be easily integrated with cropping to supress many dominant weeds (Eslami, 2015; Mahajan et al., 2015). Under high weed pressure situations, there can often be crop yield benefits, better weed control, and reductions in cost of weed control by adopting dense crop stands (Mahajan et al., 2015). Increasing plant density would lead to early canopy closure and thereby limit light penetration into the inter-row spaces and lead to the suppression of many dominant weeds (Eslami, 2015). The weeds that proliferate under a non-competitive environment, but perform poorly under increased competition, could be effectively suppressed by integrating this tactic (Chauhan and Johnson, 2010b; Eslami, 2015). *Cyperus* sp. and *Echinochloa* sp. were supressed in rice by adopting this tactic (Chauhan and Johnson, 2010b); these results are important as *Cyperus* sp. and *Echinochloa* sp. are also dominant weeds of cotton growing regions across the world (Table 1).

In the case of cotton planted at 1 m row spacing, the planting density followed is 8–12 plants m^{-2} and 6–9 plants m^{-2} for irrigated and dryland cotton, respectively (Hake et al., 1991; Wright et al., 2000). In cotton, a varying plant density is achieved by narrowing rows spaces, skipping crop rows or by planting in paired row. In the conventional system, cotton is planted at a row spacing of 1 m and generally a density of 100,000 to 120,000 plants ha^{-1} is followed, whereas in narrow row (38–76 cm) or ultra narrow row (19–25 cm) systems, there may be an increase in plant density compared to the standard row planting (Hake et al., 1991; Jost and Cothren, 2000; Wilson et al., 2007). Some studies have shown weed management and yield advantages in crops by following narrow rows by using the same plant density as in wide rows (Chauhan and Johnson, 2010a; Dusabumuremyi et al., 2014). Through future research, the weed management and yield benefits of narrow row systems by following the same plant density as in standard row systems could be evaluated in different cotton producing zones.

From a weed management viewpoint, there would be early canopy closure in ultra-narrow row cotton, more light interception, and weed suppression (Jost and Cothren, 2000; Wilson et al., 2007). In a study at Alabama, when the leaf area index (LAI) was correlated with cotton phenology, cotton reached a LAI of 1 within 5 weeks and a value of 5 coinciding canopy closure was achieved in within 12 weeks after planting (Ashley et al., 1965), but in the narrow row system, the canopy closure can be much earlier (Jost and Cothren, 2000; Wilson et al., 2007). The narrow row configuration of 19 cm with a plant density of around 40 plants m^{-2} achieved 51% and 92% of canopy closure by 49 and 61 days after planting, respectively (Jost and Cothren, 2000). The corresponding values for the wide row of 1 m with a planting density of 10 plants m^{-2} were 20% and 32% (Jost and Cothren, 2000). There will be differential morphological changes with increased density as a competition response and search for more sunlight, plants will increase in height in thicker stand over thinner stand at the early crop growing phase and help the crop to have a comparative advantage over weeds at the beginning phases of crop growth (Hake et al., 1991; Jost and Cothren, 2000).

Studies conducted in the USA indicated significant weed suppression due to narrow row spacing (Table 2). In a study, a 35% reduction in weed biomass was achieved from twin-rows spaced at 38 cm compared to 102 cm standard row. Similarly, significant weed suppression was achieved in cotton planted at 25 cm and 75 cm row spacing compared to 102 cm rows (Gwathmey et al., 2008). In another study in Florida, two row spacing, 76 cm and twin row spacing (19 cm between rows and 76 cm between two sets of rows) both at a density of 7 plants m^{-2} were compared (Stephenson and Brecke, 2010). Better weed management and yield were achieved from the twin-rows system compared to the single row system. *C. benghalensis, S. obtusifolia,* and *Jacquemontia tamnifolia* (L.) Griseb. Iaqta control was better in the twin-rows system compared to the single row system. This was due to the rapid canopy closure and better light interception under the twin-rows system than the single row system (Stephenson and Brecke, 2010). In all these studies, significant weed suppression was achieved due to early canopy closure and competition for resources and light. The weed suppression would further enhance herbicide efficacy or reduce the further application of herbicides at the later part of the crop growth (Culpepper and York, 2000).

In the conventional standard row cotton system, multiple applications of post-emergent herbicides are required to achieve a reasonable level of weed control along with the pre-emergent herbicides (Culpepper, 2006; Norsworthy et al., 2007). However, in narrow row systems, the pre-emergent herbicide would take care the initial weed growth and there can be increased herbicide efficacy of post-emergent herbicides (Culpepper and York, 2000). In a study conducted in North Carolina, *Brachiaria platyphylla* Griseb., *X. strumarium*; *C. album, Ambrosia artemisiifolia*, *Eleusine indica, D. stramonium,* and *Amaranthus palmeri* were controlled by a pre-emergent application of pendimethalin plus fluometuron followed by glyphosate as early post-emergent (Culpepper and York, 2000). In addition, herbicides would be more effective under the narrow row system compared to the standard row system as weed vigour will be less due to the increased competition from cotton plants under the narrow row system (Culpepper and York, 2000). In a study conducted in Arizona, an application of glyphosate under ultra narrow row achieved a higher level of *Portulaca oleracea* L. control than standard row cotton (McCloskey et al., 2000). This was because the herbicide application coupled with early canopy closure led to severe stunting and suppression of this weed. A consultant survey in the USA indicated narrow row spacing as an important management option in suppressing weeds, especially at the later weed emergence and growth stage (Riar et al., 2013b).

Other than weed control benefits, narrow row and ultra-narrow row configurations could provide yield advantages (Balkcom et al.,

Table 2
Weed management benefits due to narrow row spacing.

Treatments compared	Weed control benefits	Yield benefits	Reference
Cotton planted evenly at 102 cm row was compared with twin rows cotton at 38 cm and separated at 102 cm	35% reduction in weed biomass in the twin rows system at 11 weeks after planting	6% higher lint yield from twin rows system	Reddy and Boykin, 2010.
Cotton planted at 25 cm, 76 cm and 102 cm rows.	*Amaranthus retroflexus* L was supressed significantly under 25 and 76 cm row spacing compared to 102 cm spacing	Weed interface on yield was not studied	Gwathmey et al., 2008
Cotton planted at 38 cm and 76 cm rows	Weed suppression rating was 99 and 89 for 38 and 76 cm row spacing, respectively [a].	Weed interface on yield was not studied	Gwathmey et al., 2011
Cotton planted evenly at 76 cm, and twin row spaced at 19 cm, and separated at 76 cm.	At a uniform plant density of 7 plants m^{-2}. Weed suppression rating was 86 and 92 for 76 and 19 cm, respectively[a]	Lint yield was 980 and 1200 kg ha^{-1} for 76 and 19 cm, respectively	Stephenson and Brecke, 2010

[a] Weed suppression scale was 0 for no weed control, and 100 for total weed control.

2010; Jost and Cothren, 2000). However, soil properties and rainfall characteristics can vary over years and also the associated yield benefits (Balkcom et al., 2010; Jost and Cothren, 2000). The limitation of this system is that at the beginning, the moisture requirement would be high as early thick stand demand more moisture whenever a high seed density is followed under narrow row cropping (Knowles and Cramer, 1999). With the advancement in the sprinkler and overhead systems, better irrigation efficiency and irrigation in tune with crop requirements could be met. Narrow row spacing is not widely practised in Australia. Trials conducted at different locations indicated differential yield response due to narrow row cotton, the yield advantages were not always observed for narrow row cotton compared to 1 m row spacing across different locations. However, rapid canopy closure and weed suppression was a common observation (Roche et al., 2003, 2006). The lack of yield response at certain locations and during certain years clearly indicated the interaction of a dense plant population and the available resources with the environment to achieve any desirable results. In China, a high density planting technique is followed by integrating various agronomic management such as drip irrigation and plastic mulching (Dai and Dong, 2014). The plant density of 200,000 to 300,000 ha^{-1} are maintained, and yields of more than 1800 kg ha^{-1} is achieved by this cultivation technique. In China, it is called "short-dense-early" technique. The advantages are, early crop, better weed control over the standard row system, water saving, less cultivation cost, and avoidance of terminal drought.

In some situations, intermediate row spacing may be advantageous regarding crop yield and weed control. In a study, there was a significant yield advantage for 76 cm row spacing compared to 25 and 102 cm row spacing (Gwathmey et al., 2008). Weed suppression in 76 cm row spacing was on par with 25 cm and superior to 102 cm row spacing, indicating planting in intermediate rows can be more effective in terms of yield and weed suppression (Gwathmey et al., 2008). The results of this study are very pertinent and indicate that the benefits of narrow row and high plant density can vary with locations.

5. Crop row orientation as a weed management tactic

Crop competitiveness for light can be improved by orienting the crop to intercept more sunlight and increase shading of weeds, thus supressing their growth. The use of row crop orientation to maximise crop yield and supress weed growth has been reported in wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) (Borger et al., 2010, 2016), and sugar beet (*Beta vulgaris* L.) (Anda and Stephens, 1996). Orienting crop rows in a nearly perpendicular angle to incident sunlight maximises light interception by crops (Mutsaers, 1980) and with less light penetrating the interspaces, less light is available to weeds. Interception of reduced red to far-red light ratio (R/FR) induces a series of physiological and developmental adjustments including reduction in stem diameter, suppression of branching, and changes in biomass partitioning (Afifi and Swanton, 2011; Ballare et al., 1987, 1990; Smith, 1982). Maximising light interception by row orientation is dependent on latitude and seasonal tilt of the earth in relation to the sun (Mutsaers, 1980). Models by Mutsaers (1980) estimated that near the equator, north-south (as opposed to east-west) gave the highest absorption all year round. At higher latitudes (up to 55°) absorption was highest with north-south during the summer and east-west during the rest of the year. Beyond 65°, the east–west orientation gave the greatest light absorption all year (although the difference between orientations is minor) (Mutsaers, 1980).

Cotton is grown between latitudes 45° north and 30° south (ICAC, 2007). As initial weed management in cotton is important, it would be better to adopt row orientation pertaining to the planting season. As an example, in Australia, cotton season begins in spring and ends in autumn. As Australian cotton growing area falls between latitudes 15° and 35° south, it may be better to plant east-west direction to have the advantages early in the season. However, this hypothesis needs testing as the proximity of cotton growing regions to equator can vary. In addition, the interaction of landscape slope with row orientation particularly in furrow-irrigated cotton may also be researched. Moreover, when tested, the advantage due to row orientation was better in wheat and barley compared to broad-leaved crops including canola (*Brassica napus* L.), field peas (*Pisum sativum* L.), lupin (*Lupinus angustifolius* L.) and sunflower (Borger et al., 2010). Similar to these broadleaved crops, cotton leaves are diaheliotropic (Ehleringer and Hammond, 1987; Lang, 1973), altering their angle over the course of the day to remain perpendicular to the sun's direct rays. Therefore, more research is required on this topic.

6. Recommendations of the analysis and future research priorities

There is a considerable similarity in weed flora of cotton growing regions across the cotton producing countries (Table 1). Many of the weeds have already developed glyphosate resistance wherever herbicides are used without diversity (Kruger et al., 2009; Shaw et al., 2009; Sosnoskie and Culpepper, 2014). Many *A. palmeri* populations have rapidly evolved resistance to glyphosate in North America (Culpepper, 2006; Norsworthy et al., 2007; Sosnoskie and Culpepper, 2014; Webster and Sosnoskie, 2010) and it is an issue that many weeds from *Amaranthacea* family are predominant weeds in the cotton producing zones (Table 1). *C. canadensis* and *C. bonariensis* are present in many cotton growing regions and these weeds are difficult to manage with glyphosate (Flessner et al., 2015; Werth et al., 2011). *Echinochloa* sp. is a predominant weed in many cotton growing zones and this weed has already developed resistance to glyphosate in many agro-ecosystems (Heap, 2016). In addition, volunteer cotton (glyphosate-resistant) is evolving as a difficult weed to manage in many agroecosystems (Werth et al., 2013; York et al., 2004). Wherever herbicides are used without diversity, there could be rapid emergence of resistant weeds (Culpepper, 2006; Webster and Sosnoskie, 2010). Therefore, it is utmost important that non-chemical management strategies should be integrated with cotton cropping to ensure the sustainability of herbicides.

This analysis indicates that weed competitiveness of commercial cotton cultivars is not fully explored and understood. Cultivars can vary in their weed competitiveness and not all commercially available cultivars are good weed competitors (Liu et al., 2015; Rezakhanlou et al., 2013). In addition, early seedling vigour was poorer for many commercial cultivars compared to many new breeding lines (Liu et al., 2015). Therefore, more research on the weed competitiveness of commercial cultivars is required as that would give growers the choice of best cultivars under high weed pressure. In addition, future breeding research may focus on early seedling vigour and crop competitiveness along with yield attributes and resource use efficiency.

Undoubtedly, studies conducted worldwide clearly indicated the weed management benefits of increasing plant density (Balkcom et al., 2010; Jost and Cothren, 2000). It is to be emphasised that narrow row system or increasing planting density could be supplementary to the prevailing herbicide-based weed management rather than replacing the herbicides totally. The approaches would enhance herbicide efficacy of both pre-emergent residual herbicides and post-emergent herbicides thereby reduce multiple applications of herbicides (Culpepper and York, 2000). The adoption of this technology is low in countries like Australia.

Irrespective of the system of planting, there would be an optimum plant density per unit area that the resources and environment could support. Therefore, based on soil, rainfall, water resources, and the prevailing weeds, the optimum density need to be researched and evolved. Yield advantages cannot always be warranted (Roche et al., 2003, 2006). However, studies clearly indicated the weed suppression by narrow row spacing (Balkcom et al., 2010; Jost and Cothren, 2000). As narrow row offers more competition this system would offer efficient and sustainable weed control (Culpepper and York, 2000), thereby, multiple applications of post-emergent herbicides can be minimised. However, to increase the adoption, management options need to be revised for narrow row cotton. There should be assured irrigation at the beginning of the cropping season as the moisture requirement of a thick plant stand will be high (Knowles and Cramer, 1999). In addition, in sandy soils, a high density system may not yield desired results due to less soil moisture storage in tune with rapid plant growth (Knowles and Cramer, 1999). The interaction of other weed management options and herbicides should be evaluated. Rotating cotton with crops of high residue cover would reduce early emergence of weeds and integrating this with narrow row spacing would yield desired results as late emerging weeds may have to face intense competition from cotton (Price et al., 2012, 2016).

Many studies reported earliness in crop harvest under narrow row systems (Knowles and Cramer, 1999). Early narrow row cotton would reduce terminal drought and also suit to adjust the planting dates. In addition, micro-meteorology in the crop zone can vary and that may have the desired effect to thrive heat waves. Overhead irrigation systems would ensure irrigation efficiency and ensure irrigation in tune with early crop establishment and suited to no-till narrow row systems. The efficacy of herbicides under over-head irrigation systems compared to flooding needs to be researched. This is important as there would be continuous flow of water from one end to the other end of the field under flood irrigated cotton, and thereby, residual herbicide efficacy may be reduced. A narrow row production system using herbicide-tolerant cultivars under no-till in rotation with cereals or other cover crops could be evolved after research trials.

7. Summary

Based on the current analysis, increasing plant density and reducing row spacing would supress weeds. In addition, such options would reduce herbicide selection pressure and supplement the herbicide-based weed management, thereby, delay the evolution of resistant weeds. It is to be emphasised that a narrow row system or an increasing planting density could be supplementary to the prevailing herbicide-based weed management rather than replacing herbicides totally. High planting density and narrow row spacing in cotton would not only supress weeds but also enhance herbicide efficacy and reduce multiple applications of herbicides. However, more research is required to arrive at the optimum plant density and ideal row spacing to be followed, as there can be differences in soil, environment, weed populations, and cultivars across different agroecosystems. Not all the commercially available cultivars are scientifically screened for their weed-competitiveness, and future breeding should aim for weed-competitive cotton cultivars along with yield attributes and resource use efficiency. Similarly, more studies are required on the orientation of crop rows, as any initial competitive advantage of crops over weeds would be highly desirable in cotton weed management. Many of the methods discussed here such as crop density, cultivars, and row orientation can be adopted easily and can be integrated with the current practices.

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