# CHAPTER II
# LITERATURE REVIEW

## 1. Pre-rice growing conditions and the risks of waterlogging

Rice-based crop systems are characterized into three major groups: 1) upland, 2) irrigated lowland and 3) rainfed lowland. In general, the growing season of lowland paddy fields can be divided into the dry season, the pre-monsoon moist period, the wet period, and the post-monsoon moist period (Zandstra, 1982). In Northeast Thailand, where a bimodal rainfall pattern occurs, or where there is an early and gradually increasing monsoonal rainfall, planting of upland crops before lowland rice can be done (Lantican, 1982). Soil moisture during the transition between dry season and pre-monsoon moist period can be utilized for upland crop production, where rice is transplanted later, during the peak period. The growing period starts at the onset of the rainy season and ends when the soil is saturated. According to Zandstra (1982), factors determining the length of pre-monsoon or pre-rice crop growing period depend on: i) the length of the monsoon period when the early start of the rain leads to a long pre-monsoon moist period, ii) soil texture where light sandy soil has a longer pre-rice crop growing period than heavy soil such as clay or silt clay because it is more readily to saturated with water due to the reduced percolation rate and iii) field location where field topography determines the availability of lateral water movement to adjacent lowland paddy fields. Higher field positions can be completely drained and thus have greater potential for long pre-rice crop growing period.

The important climatological factors during the pre-rice growing period are short growing period for at least 60-90 days, longer photoperiod, prevailing cloudiness, excessive wetness during the flowering to maturity stage and intermittent water stress (Lantican, 1982). Three major problems associated with upland crop production in early rainy season are (i) waterlogging due to the heavy rain on typical poor surface and poor internal drainage, (ii) intermittent drought stress due to erratic rainfall and (iii) pest and disease, particularly for legumes crops.

Waterlogging is the predominant constraint of growth and yield of upland crop in most situations. Under field conditions, there are generally rising water table, low evapotranspiration (Polthanee, 1997), limited external drainage due to insufficient paddy to paddy slope gradient and slow infiltration because of the typically fine texture of puddlled and bunded paddy fields (Herrera and Zandstra, 1979). These lead to waterlogging, which is followed by intermittent and prolonged shallow surface flooding toward the peak rainfall in mid rainy season.

## 2. Crop management for pre-rice upland crop production

### 2.1 Crop species and variety selection

According to previously mentioned climatological conditions, it is reported that crops growing during pre-monsoon moist period usually produce more stover relative to seed yield (Lantican and Garaza, 1977). The key characteristics of successful crop for pre-monsoon moist period are early maturity or determinate crop to minimize the acute stresses late in the growing season, waterlogging tolerance, and drought tolerance at early growth stage (Lantican, 1980). In addition, harvesting as a green vegetable instead of a grain and early seedling development enables the crop to remain competitive with weed and gives the plant a good start in development before the occurrence of adverse effects or stress factors.

It has been reported that grass species are usually more flooding tolerance than legumes crops (Bolton and Mckenzie, 1946). Sorghum (Gomez and Evangelista, 1977), jute, and soybean are more flooding tolerant than maize, mungbean, and sweet potato (Villareal and Lai, 1976). The genetic variability in tolerance for waterlogging of various upland crops opens the possibilities in selection and use in breeding programs. Flooding tolerance variation among species and cultivars of following crops has been reported for maize (Zaidi et al., 2003; 2004), barley (Meechoui, 2001) and fibre crops (Changdee et al., 2008). However, crop selection for pre-rice growing condition may not only depend on its ability to withstand flooding but also its market potential, residual effect on primary rice, crop management, production cost and farmer acceptability. Sweet sorghum, which has stalk as final yield, a short growing period, is a short day and drought- tolerance crop, may possess desirable characteristics and has proven a useful crop for pre-monsoon growing period in paddy fields.

### 2.2 Planting date selection

Planting date selection is one of the critical crop management factors in successful production of upland crops before rice. In fields with no irrigation system, if crops are sown too early, the seeds may not emerge from the dry soil. If emergence does occur, the seedlings may suffer from drought stress. In contrast, if sown too late, they could suffer from waterlogging and severe flooding throughout growth cycle, especially during the reproductive period. Choosing an optimum planting date together with a waterlogging tolerant crop species or cultivars would help alleviate the damage due to waterlogging and increase the productivity of a pre-rice crop.

In the Philippines, Polthanee (1989) found that early planting mungbean had 16 % higher grain yield than late planting under ridge planting methods. And early planting grown on flat (no ridging) soil had a 42% higher grain yield than late planting date. This indicated that if waterlogging tolerant crops are not available and field drainages cannot be done, early planting date is the best strategy to improve crop yield.

In addition, with irrigation systems, early planting also provides an opportunity to have a long growing season and even provide the intensive land use by introduction a new triple-cropping pattern, field crop-rice-field crop or by using short-duration field crops.

## 3. Existing pre-rice cropping patterns under rainfed and irrigated conditions in Northeast Thailand

In order to increase yield per unit land and per unit time, farmers in Northeast Thailand have long adopted a double cropping by planting pre-rice crops. The productivity of these systems relies on the reliability and amount of early wet season rainfall and on access to supplementary irrigation from either stored surface water or shallow ground water. Specific biophysical and socioeconomic factors determine cropping patterns at each location (Limpinuntana, 2001; Polthanee, 2001). Under rianfed conditions, pre-rice crop production is successful under reliable rainfall and shallow ground water conditions (Polthanee and Marten, 1986; Polthanee, 2001). Nevertheless, with the ability to access supplemental irrigation, dry-season cropping is becoming more common in Northeast Thailand (Pandey, 1998; Polthanee, 2001).

### 3.1 Rice-based cropping systems under rainfed conditions

Crop production during rainy season in these areas relies on Southwest monsoons and cyclones, typically originated from the Indian Ocean. The rainy season is from March to October with a bimodal pattern. The first peak of rainfall is from May to June and the second from July to October. The traditional early wet season crop planted in this area is sesame and kenaf (Polthanee and Marten, 1986; Polthanee, 2001). The strategy used to achieve high yield pre-rice crops under rainfed conditions is early planting in areas having shallow ground water. Land should be prepared during the last week of April or during the end of the previous rainy season. Sesame is planted at the first rain during February-April and relies on soil moisture derived from shallow ground water and erratic rain. Plants are harvested during intermittent dry season (June-July) before transplanting of normal rice. For kenaf, early planting is advantageous for long crop growth duration, resulting in high fibre yield. Kenaf is normally harvested in August. Kenaf may suffer from flooding at late growth stage but with its waterlogging tolerant capability via its production of aerenchymatous adventitious roots (Changdee et al., 2008), growth and yield are only slightly affected (Polthanee, 2001).

### 3.2 Rice-based cropping systems under irrigated conditions

According to Polthanee (2001), irrigation systems in Northeast Thailand rely on three sources of water; shallow-wells; farm ponds; and state irrigation facilitated by dams, reservoirs and main rivers. The common cropping patterns in irrigated areas are photosensitive rice followed by non-photosensitive rice or field crops (Limpinuntana, 2001). Crop selection is primarily influenced by market potential and subsidies from private companies. In general, under shallow-well and farm pond irrigation system, field crops with short life cycles are planted such as tobacco, garlic, chili, tomato, onion, cabbage, sugar beet and baby corn (Polthanee, 2001). However, in some years with severe drought, these crops were not planted due to insufficient water. These crops are normally planted in December and harvested in April. Although state irrigation systems can provide the required high amount of water, they cover limited areas. After harvesting major rice, secondary rice may be planted during January-February and harvested at April- May. In addition to secondary rice, field crops such as peanut, soybean, mungbean, maize, watermelon or vegetables are usually grown. However, with the severe drought currently occurring, crops with high water requirement such as secondary rice or soybean suffer from drought stress and are not recommended by the government of Thailand. With fluctuation in production and prices of these crops, they are not attractive to farmers.

**4. Soil flooding and other damaging features of flooded soil**

Waterlogging is defined as a condition of the soil where excess water limits gas diffusion. It could be part of the root zone or up to the soil surface, while flooding means only when the water level is above the soil surface (Pradet and Bromsel, 1978; Setter and Waters, 2003). Hypoxia is characterized by the limited availability of oxygen for oxidative phosphorylation or partial oxygen deficiency (0%-20.9% at 20 ◦C), where there are occurrences of increased anaerobic metabolism, increased ATP production through glycolysis and increased NAD+ regeneration via lactate and ethanolic fermentation. Under this condition, cellular ATP production per molecule of glucose is low. The term anoxia refers to complete oxygen deficiency (0% at 20◦C). Anaerobic metabolism, NAD+ regeneration via lactate and ethanolic fermentation and ATP production occur solely via glycolysis. In this process cellular ATP is low whereas ADP content is elevated (Bailey-Serres and Voesenek, 2008).

When water saturates the soil pores, gas spaces are filled. This leads to the modification of several soil physical-chemical characteristics (Kirk et al., 2003; Dat et al., 2004). The first event is the slow influx of oxygen due to the 10,000 times slower gas diffusion in water compared to air (Armstrong, 1979).This small amount of oxygen is quickly consumed during the early stages of flooding by aerobic organisms in the soil and roots, resulting in a shortage of oxygen. In addition, excess water in the soil pores also inhibits the diffusive escape and/or oxidative breakdown of gases such as ethylene (Arshad and Frankenberger, 1990) or carbon dioxide. These are produced by roots and soil micro-organisms leading to increased concentration of ethylene and $CO_2$ in the root environment, which have considerable effects on plants' metabolism, anatomical and morphological characteristics.

Furthermore, under the absence of oxygen micro organisms, utilize other inorganic ions as alternative electron acceptors to sustain their respiration causing subsequent changes in soil biochemistry (Ponnamperuma, 1972). Firstly anaerobes chemically reduce nitrate, converting it to nitrite, nitrous oxide and nitrogen gas (denitrification), resulting in losses of nitrate from root rhizosphere. As the reducing intensity of the soil further increases obligate anaerobes chemically reduce oxides of $Mn^{4+}$, and $Fe^{3+}$ to form highly soluble $Mn^{2+}$ and $Fe^{2+}$ (Laanbroek, 1990), which are toxic to plants. If flooding is prolonged, anaerobic bacteria may then convert $SO_4^{2-}$ to $H_2S$, a poison of respiratory enzymes and non-respiratory oxidases. In the most severely reducing soils, methogenic bacteria can use some energy stored in organic soil compounds by fermenting organic matter to carbon dioxide and methane, most commonly known as green house gases. The changes in soil chemistry by microorganisms under flooding are shown by redox potential (Eh). The lower Eh, the less oxygen there is. Eh under aerobic conditions ranges between +380 to -280 mV (Patrick and Reddy, 1978), whereas aerobic soil measures +800 to +400 mV (Ponnamperum, 1984).

Soil pH is also strongly affected by soil waterlogging. Generally, soil pH tends to increase toward neutrality (6.7-7.2) due to the dissolution of carbonate and bicarbonate during the early waterlogging period (Lu et al., 2004). The pH of alkaline soil declines and pH of acid soil increases. The changes in pH due to flooding may take up to several weeks; depending on soil type, organic matter level, microbial population, temperature and others soil chemical properties. Changes in soil pH affect the turnover of soil organic matter and mineralization, nitrification and urea hydrolysis (Probert and Keating, 2000). Increased pH in flooded soil affects phosphorus availability by changing from $H_2PO_4^-$ (pH lower than 6.8) and $HPO_4^{2-}$ (pH 6.8-7.2), the most available form for plants, to $PO_4^{3-}$ (pH greater than 7.2), which cannot be used by plant at all. Generally, flooding increase availability of phosphorus. However, if the soil is higher in Fe and Al, P can be adsorbed by clay particles. This results in temporary decrease in P availability. Clay loam soil, therefore, has lower P availability than sandy loam soil, given the same pH value, but had higher Fe and organic matter (Ponnamperuma, 1972). Another effect of flooding is to change soils physical properties.

Waterlogging increases the number of small soil particles by the breakdown of large aggregates. This can be seen after the water is drained. The result is dense structure, small soil pore diameters, higher mechanical resistance to root penetration, low $O_2$ concentration and the inhibition of resource uses due to the rearrangement of these small parts. In high permeability soil, particularly soil with high sand content, flooding increases nutrient loss by leaching. In addition, a decrease in soil temperature under flooding was found to retard germination, seedling growth and nutrient absorption (Ponnamperuma, 1984).

There are several factors affecting the onset and intensity of waterlogging including; soil type (Setter and Water, 2003), land use (Samad et al., 2001), respiration rate of plant roots and organisms, and the solubility of $O_2$ in water (Thought and Drew, 1982). Usually, anaerobisis requires hours or days to develop when the soil is waterlogged (Setter and Waters, 2003). In some waterlogged soils, anaerobic conditions may never occur due to low biological activity, low temperature, ability of plants or movement of water by percolation and various combinations of all the above factors (Grable, 1966).

## 5. Physiological effect of flooding on plant

### 5.1 Water uptake

Under flooding conditions, the abundance of water surrounding plant roots affects the water balance of plant detrimentally. In particular, flooding reduces the ability of roots of sensitive species to take up water. This response can start within 2-6 h after initiation of flooding. Leaf water potential and relative leaf water content (RLWC) are generally used as the means of measuring water status of plants. In grain sorghum, Orchard et al., (1986) reported that the effect of flooding on leaf water potential depends on the growth stage at which it occurs. Leaf water potentials were maintained close to those of the controls when waterlogging was applied at vegetative and anthesis growth stage. But a relative increase in leaf water potential over the control was found when waterlogging was applied at initiation. Sorghum exhibits a few signs of water uptake inhibition by leaf rolling, which was noted only at 8 d after waterlogging at initiation stage (Orchard et al., 1986). A decrease in leaf water potential under anaerobic conditions has also been reported in flooding sensitive lupin (*L. luteus*) (Davies et al., 2000).

The exact explanation for decreased water uptake under anoxic conditions is not yet clear but a decrease in root hydrolic conductance or root permeability to water has been proposed as the key reason. The decreased water permeability of roots leads to a decrease in leaf water potential and thus lower stomatal conductance. Therefore, it reduces transpiration, stomata closure and reduces the amount of water up take by roots (Nilsen and Orcutt, 1996). However, how anoxic conditions affect root permeability remains elusive. Recently, Tourmaric-Roux et al. (2003) demonstrated that decrease in root hydrolic conductance results from a disruption of aquaporin functioning by the cytosolic acidosis induced by anoxic conditions.

**5.2 Nutrient uptake and translocation**

Flooding significantly affects the nutrient relationships of plants by three main categories. Firstly, flooding reduces transport of water and will reduce transport of nutrients to leaves. Secondly, anaerobic conditions reduce the abundance of ATP (Adenosine triphosphate) which is utilized in active nutrient uptake. Finally, flooding changes the availability of important nutrients (Nilsen and Orcutt, 1996). With regard to the first mechanism, inhibition of water uptake under flooding condition reduces water transport and transpirational water flow and hence decreases mass flow of nutrients into the roots. Nevertheless, due to the selective permeability of root cells to ions, insufficient energy generation in roots during anaerobic conditions is more crucial to plant nutrition balance. It has been shown that when the soil is flooded a switch from aerobic respiration to anaerobic respiration yields only 2 to 4 mol ATP per mol hexose compared with 30 to 36 mol ATP by aerobic respiration (Taiz and Zieger, 2002). However, a selectively permeable barrier of plasma membrane in plant cell requires ATP to transport protons, inorganic ions, and organic solutes across the plasma membrane. Recent studies indicate that lack of ATP will decrease nutrient uptake from soil solution to roots and impair translocation from roots to shoots resulting in nutrient deficiency in plant tissues (Davies et al., 2000; Malik et al., 2001; 2002).

In sorghum the effect of waterlogging on nutrient uptake depends on the growth stage at which waterlogging occurs. Waterlogging at vegetative stage and initiation stage reduce N P and K uptake in waterlogged plants. However, waterlogging at anthesis stage has no significant effect on nutrient uptake of sorghum. Total and seed phosphorus are greatly affected by waterlogging. It has been reported that in grain sorghum inhibition of nutrient uptake results in yellowing of leaves (Orchard et al., 1986), indicating the transportation of mobile nutrients; N, P and K, from oldest leaves to the ones that are actively growing (Trought and Drew, 1980). The decrease in nutrient uptake by waterlogging in sorghum was attributed to the reduction in root growth, referring to the lower root surface for nutrient uptake (Orchard et al., 1986).

**5.3 Stomatal closure**

Adjustment of stomata is important for the regulation of water loss by transpiration and for controlling the rate of carbon dioxide ($CO_2$) uptake necessary for $CO_2$ fixation during photosynthesis in plants. Stomata closure under dry conditions is the mechanism utilized to avoid dehydration. Under flooding stress, stomata closing is also proposed as a mechanism for regulating the water balance of plants and preventing leaf dehydration (Asharf, 2003).

In grain sorghum, Orchard et al. (1986) reported that waterlogging induced stomatal closure after the first day of waterlogging, resulting from the increase in stomatal resistance. This indicates that sorghum possesses the ability to acclimate to the stress. Even though stomatal closure is the strategy to overcome water stress in plants, permanent closure results in restriction of $CO_2$ and biomass accumulation. Several researches have revealed that sensitive species/genotypes firstly reduced their stomatal conductance in response to flooding, such as in wheat (Malik et al., 2001), while in flooding tolerant cultivar leaf conductance did not change i.e. ruzigrass *(Brachiaria brizantha*) (Dias-Filho, 2002), perennial ryegrass (*Lolium perenne* L.) (McFarlane et al., 2003) and barley (Pang et al., 2004). Zaidi et al. (2004) indicated that partial stomatal closure was the physiological trait associated with excess moisture tolerance in maize.

Mechanisms responsible for stomata closure under poor root aeration are not fully understood. The suggested mechanisms are mediated by plant hormones, changes in K, increase in internal $CO_2$ and change in leaf water potential. These were referred to as related to alteration of root permeability to water and nutrient. Earlier researchers have reported that potassium (K) is a critical factor in stomatal closure due to the rapid decrease in K uptake and in leaf K concentration under anoxic conditions (Drew and Sisworo, 1979; Throught and Drew, 1980). More recently much attention has been focused on leaf water potential (Davies et al., 2000; Mollard et al., 2008) and plant hormone, particularly abscisic acid (ABA) (Jackson, 2004; Ahmed et al., 2006; Else et al., 2009).

**5.4 Photosynthesis**

Soil flooding reduces photosynthesis rate "A" of many plant species, particularly of flooding-intolerant species or cultivars. Pang et al. (2004) indicated that photosynthesis rate could be a useful tool to evaluate flooding tolerance among cultivars or species. Several researchers have found that the photosynthetic rate of flooding sensitive cultivars was greatly suppressed by flooding but less effects on A was found in flooding tolerant cultivars (Davies et al., 2000; Dias-Filho, 2002; McFarlane et al., 2003). Ahmed et al. (2002) indicated that after 8 d of waterlogging a higher reduction of photosynthetic rate of mungbean was found in flooding intolerant cultivar (64-82% reduction) than flooding tolerant (58-76% reduction).

In general, the pattern of A decreases over time, the longer flooding duration, the higher A reduction as compared to the control. There is evidence that the rapid decrease in A indicates a higher flooding sensitivity of plants. In wheat (Malik et al. 2001) and mungbean (Ahmed et al., 2006) flooding at vegetative stage reduced A to 25% within 24 h compared to the control. A was further reduced to zero at 5 d after waterlogging in wheat, while mungbean could maintain A to a higher level than wheat. The ability to maintain longer photosynthetic rate during flooding in flooding tolerant but not flooding sensitive genotypes has been also reported in *Lotus corniculatus* (Striker et al., 2005) and lucern species (Irving et al., 2007). Nevertheless, in some species flooding greatly reduces A at early flooding but A is elevated after prolonged flooding duration indicating plant acclimation to anoxic conditions such as *Lepidium latifolium* L. (Chen et al., 2005). In sugarcane, Glaz et al. (2004a) reported that a short period of flooding for 7 d and high water table did not affect or even enhance photosynthetic rate. None of the research reports the effect of waterlogging on photosynthesis of sweet sorghum. However, the reduction in leaf photosynthetic rate by drought stress has been reported elsewhere (Massacci et al., 1996).

Several studies have indicated that a decline in photosynthesis under flooding was attributed to stomatal closure (Bradford, 1983; Huang et al., 1994b; Ahmed et al., 2002; Pang et al., 2004). Nevertheless, there was evidence that non-stomatal limiting regulated photosynthesis such as tropical forage grass (Baruch, 1994), mangroves (Pezeshki et al., 1997) and sugarcane (Tetsushi and Karim, 2007). Factors other than diffusional limitations include leaf chlorophyll content (Bradford, 1983; Huang et al 1994b; Irving et al., 2007), ethylene production (Ahmed et al., 2006), amount or activity of photosynthetic enzymes (Huang et al., 1994a,b), sink demand, also known as feedback inhibition of photosynthesis caused by accumulation of carbohydrate in leaf (Limpinuntana and Greenway, 1979; Wample and Davis, 1983), and by cessation of root growth (Malik et al., 2001; Pang et al., 2004 ) and changes in chloroplast resulting in smaller grana and degradation of thylakiod membrane structure such as in some mangroves (Naidoo, 1983).



**6. Effect of flooding on plant growth**

**6.1 Roots growth**

Under flooding conditions, the gas diffusion rate is 10,000 times slower than in air (Jackson, 1985). Consequently, flooded soil rapidly develops anoxic conditions due to the complete consumption of the small amount of oxygen by aerobic soil organisms and roots. When roots of higher plants are under anoxic conditions, their growth cease and eventually the root cells die, particularly in flooding intolerant species. The effects are greatest on genotypes with greater root growth potential (McFarlane et al., 2003).

In sorghum, the effect of waterlogging on root growth depends on the growth stage of plants and duration of waterlogging (Orchard and Jessop, 1985; Pardales et al., 1991). Orchard and Jessop (1985) reported that the duration of waterlogging up to 9 d at vegetative growth stage had no significant effect on root length and root dry weight of plants but at later growth stage waterlogging reduced fibrous root growth. Waterlogging at initiation stage for 3 d had no significant effect on the root length and root dry weight of sorghum but prolonged waterlogging duration to 9 d resulted in 28% and 43% root length and root dry weight reduction, respectively. The adverse effect of waterlogging on sorghum root growth decreased when applied at late growth stage (anthesis stage) (Orchard and Jessop, 1985). On the other hand, Pardales et al. (1991) indicated that continuous waterlogging for 21 d significantly decreased both the root number and length of nodal, first order and second order lateral roots. Seminal root development of sorghum was restricted by periodic waterlogging for 9 d and 12 d. The decrease in root length was mainly due to the apical disintegration of the older nodal roots beginning from day 15 onwards.

The possible causes of death in anoxic cells include self poisoning by cytoplasmic acidosis (Taiz and Zieger, 2002), fermentation end products, insufficient energy generation to sustain cell integrity (Jackson, 2004) and flooding- induced phyotoxins such as ethylene or carbon dioxide (Boru et al., 2003) and high solubility of $Mn^{2+}$, $Fe^{2+}$ and $H_2S$ (Jackson, 2004).

**6.2 Shoot growth**

Waterlogging affects the two main factors controlling biomass production, leaf photosynthetic rate and leaf area. The effect of waterlogging on sorghum depends on the growth stage at which it occurs and the duration of waterlogging (Orchard and Jessop, 1984; Pardales et al., 1991). In terms of leaf growth, 3 d of waterlogging reduced leaf growth of waterlogged plants by decreasing leaf area and leaf expansion, while stimulating leaf senescence (Orchard and Jessop, 1984). Significant effects were noted at initiation stage which persisted until maturity. It was reported that prolonged waterlogging duration had greater impact on leaf growth. Reduction in plant height occurred shortly after imposing short-term waterlogging at all growth stages and a greater rate of elongation was noted when water was drained, resulting in similar height between waterlogged and control plants (Orchard and Jessop, 1984). However, continuous waterlogging for 21 d starting from 12 DAP significantly reduced the height of sorghum to 42% (Pardales et al., 1991). Waterlogging also inhibited normal tillering patterns and stimulated the production of late tillers. No significant effect of waterlogging found at maturity among periodic waterloggings at various growth stages indicates that sorghum could retain its growth during recovery period. However, waterloging significantly reduced shoot biomass of waterlogged sorghum up to 42% when imposed at initiation stage (Orchard and Jessop, 1984). Pardales et al. (1991)

reported that after 21 d of waterlogging shoot dry weight accumulation of waterlogged plants increased 14% over the control. This was attributed to a reduction in translocation of photosynthates to roots under waterlogging conditions.

Genotypic variation in waterlogging tolerance of sorghum has not been reported. However, in cowpea (*Vigna unguiculata*) (Umaharan et a., 1997), maize (Zaidi et al., 2004) and buckwheat (Mastuura et al., 2005), it was reported that the waterlogging tolerant cultivars are able to maintain greater leave area than waterlogging sensitive cultivars. The positive correlation between leaf dry weight and flooding tolerance has also been reported in soybean (Henshaw et al., 2007b). In cereals, leaf expansion or elongation rate is widely used as an indicator of flooding tolerance. The decrease in leaf elongation in flooded soil is usually correlated to lower flooding tolerance in grass species or cultivars (Lizaso and Ritchie, 1997; Dias-Filho and Carvalho, 2000).

**7. Effect of flooding on crop yield**

Grain yield of sorghum was significantly reduced when waterlogging was applied at initiation stage, followed by waterlogging at vegetative stage. Lowest yield was obtained when waterlogging was applied at anthesis stage. The reduction in grain yield in sorghum by waterlogging was due to a reduced seed number (Orchard and Jessop, 1984). Nevertheless, in sweet sorghum no research to date has reported the effect of waterlogging on stalk yield and yield contributing factors. Under drought stress, it has been reported that growth of sweet sorghum was moderately affected by reduction in stem length; especially length of the last internode along with a relative decrease in stem width (Massacci et al., 1996). In kenaf, plant height and stem diameter are the important yield components that are suppressed by flooding (Changdee et al., 2009).

In sugarcane, it has been reported that 2 d of periodic flooding increased cane and sugar yield (Glaz and Gilbert, 2006). However, 7 d flood cycle reduced stalk yield of flooding sensitive genotype to 18%-28%, whereas yield of flooding tolerant genotypes was not affected (Glaz et al., 2004b). An increase in flooding duration to 3 months resulted in a 54%-64% reduction in cane tonnage and sugar yield (Gilbert et al., 2008). Reduction in cane yield and sugar yield by flooding in sugarcane was due to the suppression of tiller number, stalk number and stalk weight (Hasan et al., 2003; Gilbert et al., 2008). Juice quality as indicated by Brix, Pol and Purity (Hasan et al., 2003) or sucrose content were not affected by flooding (Glaz et al., 2004b; Gilbert et al., 2008). In sweet sorghum, there is lack of information about flooding effect on juice quality. However, it was reported that sucrose content in the stem of drought-stressed plants increased over the control plants (Massacci et al., 1996).

## 8. Plant acclimation mechanism under flooding conditions

Mechanisms for survival or maintenance of high biomass and grain yield during flooding have been intensively researched. The main mechanisms of waterlogging and flooding tolerance of wetland plants as well as cereals have been investigated. There were related to the ability to maintain high internal aeration through aerenchyma (Armstrong et al., 1994) and metabolic adaptation to maintain energy production under anoxic conditions (Setter and Waters, 2003).

### 8.1 Aerenchyma development

Aerenchyma is tissue with higher enlarged gas spaces than those commonly found as intracellular spaces (Visser et al., 2000; Evans, 2003). Aerenchyma is developed in the petioles, stems and roots of plants. It provides a low-resistance internal pathway for gas exchange between the plant parts above the water and the flooded tissues by improving the internal supply of oxygen (Armstrong, 1979) and facilitating the production of gases such as ethylene (Visser et al., 1997), $CO_2$, ethanol and methane (Shannon et al., 1996; Colmer, 2003). The aerenchyma also enables deeper root penetration into anaerobic soils (Laan et al., 1989). It was reported that flooding tolerant species/cultivars develop higher aerenchyma volume or root porosity (% gas volume/root volume) than flooding sensitive species/cultivars (Orchard et al., 1985; McDonald et al., 2002; McFarlane et al., 2003; Pang et al., 2004; Zaidi et al., 2004).

In sorghum, Pardales et al. (1991) reported that the ability to maintain root integrity and function of nodal roots was contributed by the formation of aerenchyma spaces in cortex layers of these roots. It was observed that just 3 d of waterlogging induced root aerenchyma development. Orchard et al. (1985) also reported that sorghum was more tolerate to waterlogging than sunflower because of its ability to maintain leaf water potential and higher root porosity. In grain sorghum, aerenchyma formation in roots is constitutive and waterlogging- inducible (Orchard et al., 1985, McDonald et al., 2002). Root porosity was noted in both fibrous root and nodal root and it increased with increased waterlogging duration. Relatively higher root porosity was found in nodal root when waterlogging was applied at initiation stage (Orchard et al., 1985). In terms of the efficiency of aerenchyma, radial oxygen loss (ROL) or the capacity of aerenchyma to provide a continuous $O_2$ diffusion to root tip are considered the efficiency of aerenchyma (Setter and Waters, 2003); McDonald et al. (2002) reported that sorghum had a low ROL, suggesting relatively low waterlogging tolerance, as compared to well-flooding adapted rice (*Orysa sativa*).

In sugarcane, it was reported that not only root aerenchyma plays a crucial role in flooding tolerance but also stalk aerenchyma (air spaces that developed in the pithy area of stalk) (Glaz et al., 2004b). Recently, Gilbert et al. (2007) reported that under 3 months long-term flooding, sugarcane genotypes with developed constitutive stalk aerenchyma up to halfway of the stalk are considered as a high flooding tolerant cultivar.

Many researchers have demonstrated that lysigenous aerenchyma formation involved in many mechanisms. It was reported that under flooded conditions, hypoxic or anoxic conditions stimulates ACC (1-amino-cyclopropane-1 carboxilic acid) synthase and ACC oxidase and produce ethylene production in roots. Ethylene induces programmed cell death (PCD) in the cortex tissue (He et al., 1996; Drew et al., 2000). The involved downstream components of this regulatory route include protein kinases, protein phosphatases, G proteins, $Ca^{2+}$, and inositol phospholipids (He et al., 1996), which transduced ethylene signal leading to cell wall breakdown. The enzymes involved in the degradation of cell wall are cellulase (He et al., 1994), pectinase and xylanase (Bragina et al., 2003).

**8.2 Adventitious root formation**

Adventitious roots (roots originating from non-root tissue) can arise in a variety of tissue locations from clusters of mature cells that renew their cell division activity. Adventitious rooting is one of the important adaptive mechanisms of wetland plants and flooding-tolerant upland crops for replacing existing roots that have been died or whose function is impaired by anoxic stress (Vartapetian and Jackson, 1997; Pezeshki, 2001). These adventitious roots provide oxygen from the environment to hypoxia or anoxia roots by directly absorbing oxygen from the surroundings and internally transport oxygen through aerenchyma (Drew et al., 1979; Laan et al., 1989). The adventitious roots can play a role in supplying water, minerals and hormones and as sinks for shoot assimilates and metabolites (Vartapetian and Jackson, 1997; Polthanee and Changdee, 2008). Flood-induced adventitious roots are usually thick and have a relatively low degree of branching, while much of the cortical cell layers are occupied by aerenchyma (Visser and Voesenek, 2004). Adventitious root is widely used as an indicator to evaluate flooding tolerance of crops. The positive relationship between flooding tolerance and the amount of rooting has been reported in flooding-tolerant species of wetland plants such as *Rumex* species (Laan et al., 1989; Blom et al., 1994; Visser et al., 1996) and upland crops such as wheat and triticale (wild wheat) (Thomson et al., 1992; Watkin et al., 1998), maize (Zaidi et al., 2004) and tribe Triticeae (Kubo et al., 2007).

In sorghum, Pardales et al. (1991) reported that immediately after imposing water, the number of nodal roots began to increase relative to the control. Nodal root number increased with a prolonged waterlogging period. Remarkable nodal root formation began from day 3, which was 47% over the control, and reached maximum at 12 d of waterlogging at 100% over the control. This increase in the number of nodal roots was due to the emergence of new nodal roots from the upper nodal position in the stem. In addition, flooding also promoted root branching. First and second order lateral roots originating from nodal roots were found. However, the production of new nodal roots in the higher nodal position were concurrent with the death of the nodal roots in the lower position, with the same sequent also happening in lateral roots (Pardales et al., 1991). Effects of waterlogging on root development depends on the stage at which waterlogging occurs. Orchard et al. (1985) reported that waterlogging at the vegetative stage delayed nodal root development to 9 d after imposing water, whereas waterlogging at initiation and anthesis stage resulted in the formation of nodal roots at 3 d of waterlogging. Pardales et al. (1991) reported that early waterlogging (12

DAP) had relatively lower nodal root number and root length than late waterlogging (24 DAP). Nevertheless, early waterlogging significantly increased lateral root development.

Flooding generates replacement root systems in cereals by stimulating the outgrowth of root primordia already present within the shoot base (Jackson, 2004). It has been reported that the induction of this new root system and their subsequent outgrowth was the interaction effects between auxin and ethylene (Visser et al., 1996; Jackson, 2004). Under flooding conditions, accumulated auxin at the base of the shoot induces adventitious root formation (Phillips, 1964). The involving interaction between ethylene and auxin for adventitious root formation is that ethylene may increase the sensitivity of plant tissues to auxin (Visser and Voesenek, 2004). However, there are possible multiple signal-transductions for adventitious root formation pathways in different species and exact environmental conditions plus other hormones such as cytokinin and gibberellin are thought to be involved (Lorbiecke and Sauter, 1999).

**8.3 Metabolism acclimation is the anoxic tolerance mechanism**

It was reported that the true tolerance mechanism is driven by the adjustment of metabolism. This includes the continued generation of ATP by glycolysis and fermentation, limited acidification of the cytosol, and amelioration of reactive oxygen species (ROS) produced during flooding or upon reoxygenation after the flood water is drained. (Bailey-Serres and Voesenek, 2008).

Acclimation to an anaerobic condition is associated with expression of the genes that encode many of the anaerobic stress proteins. These proteins are mostly glycolysis and fermentation proteins and they are transcripted and translated in high quality (Nilsen and Orcutt, 1996). Proteins and RNA that are activated by low oxygen which most of them involve in glycolysis such as sucrose synthase, pyrophosephates-dependent phosphofructokinase, kinase, enolase or in alcohol fermentation such as alcohol dehydrogenase or pyruvate decarboxylase or in lactate fermentation i.e. lactate dehydrogenase (Dennis *et al.*, 2000). In addition, superoxide dismutase (SOD) enzymes were reported as the key enzymes to deal with the consequences of the entry of ROS following anoxia (Zhu and Lin, 1995; Taiz and Zinger, 2002). This enzyme converts superoxide radicals to hydrogen peroxide, which is then converted to water by peroxidase.

## 9. Sweet sorghum

Sweet sorghum (*Sorghum bicolor* L. Moench) or sorgo belongs to tribe Andropogoneae, family Poaceae. It is one of 4 widely cultivated sorghum, grain sorghum, fibre sorghum, multi-purpose sorghum and sweet sorghum. It originated in the region of the northeast Africa comprising Ethiopia, the Sudan and East Africa (Doggett, 1988). It is considered as an extraordinarily promising multifunctional crop and a crop of universal value over other sorghum types, because it is used for food, feed and fuel purposes. In addition, it can be grown in all continents, in tropical, sub-tropical, temperate regions and in semi-arid regions. In Thailand, sweet sorghum production is still limited. However, with its high potential for ethanol production, intensive researches about sweet sorghum breeding program, cultural practice and maximum ethanol production from juice have been conducted.

### 9.1 Crop use

Sweet sorghum is an extraordinary crop. All parts of plant can be used. Grain is used for food, beer and stockfeed. Its juicy stem can be used for forage and silage (Doggett, 1988). Sweet sorghum juice has been used for the production of edible syrup (Doggett, 1970) and sugar in both USA (Schaffert and Gourley, 1982) and China (Doggett, 1988). Sweet sorghum bagasse, remaining solid residue after juice extraction, also has several uses.. Earlier, baggasse was used as animal feed or as soil fertilizer after composting with other wastes (Negro et al., 1999) or raw material for the paper industry, yielding high-quality pulp (Belayachi and Delmas, 1997). Nowadays, bagasse is mainly used for energy production by combustion (Monti and Venturi, 2003).

Recently, the use of sweet sorghum has mainly focused on ethanol production, which is directly used in a mixture with gasoline or 100% ethanol, primarily for transportation purposes. Both juice from stem and starch of grains can be used to produce ethanol. However, usually grain will be used for human food and animal feed. It has been reported that 1 t of stalk produce 70 l of ethanol on average, whereas 1 t of grain can produce up to 340 l of ethanol. Stalk yield on average 38 t ha$^{-1}$ and 2 t grain yield ha$^{-1}$, can produce ethanol from stalk 2639 l ha$^{-1}$ and 748 l ha$^{-1}$ from grain or 3,387 l ha$^{-1}$ from both juice and grain (Schaffert and Gourley, 1982). The most promising future utilization of bagasse is cellulose-based ethanol production. It is expected that with this future technology, ethanol yield ranges from 2967 to 11384 l ha$^{-1}$ depending on cultivar, location and year (Zao et al., 2009). These potential ethanol yields from sweet sorghum are comparable to the yield of ethanol from sugar beet (5060 l ha$^{-1}$), sugarcane juice (4550 l ha$^{-1}$), cassava flour (2070 l ha$^{-1}$) and higher than that from maize (1960 l ha$^{-1}$) (Rajagopal et al., 2007). Furthermore, advanced research has been conducted to produce biopolymer, value added product, (Kaewkannetra et al., 2008) or biodiesel (Gao et al., 2010) from sweet sorghum juice.

Sweet sorghum is an attractive feedstock for ethanol production throughout the world because it is a high biomass and sugar-yielding crop (Rao et al., 2004). It has a unique characteristic of high biomass accumulation (76.5 g m$^{-2}$ day$^{-1}$) (Woods, 2001) and has a special ability to accumulate high levels of extractable sugars in the stalks (Daniel et al., 1991). Unlike sugarcane, sweet sorghum is adaptable to a wide range of growing conditions. Furthermore, the advantages of sweet sorghum as sugar crop include its rapid growth rate and ability to reach maturity within 3-5 months, compared to 8-12 month in sugarcane, allowing it to be to be harvested multiple times per year, with low cost production and a seed propagation about 4.5-7.5 kg ha$^{-1}$ compared to 4.5-6.0 tons ha$^{-1}$ of stem in sugarcane, it possesses high water use efficiency, requiring 1/3 water of sugarcane, 1/2 of corn, less fertilizer and management than needed by sugarcane and sugar beet (Almodares and Hardi, 2009). It is also reported that ethanol production from sweet sorghum has lower production costs and is a cleaner energy source than sugarcane (Reddy et al., 2007c). Sweet sorghum also has a high net energy balance, 3.63 compared to grain sorghum (1.50) and corn (1.53) energy balance (Wortmann et al. 2008). It is reported that if both sugar and seeds were used as food, the energy and greenhouse gas expenditures could be compensated by producing second generation ethanol from the bagasse. Sweet sorghum could contribute to greenhouse gas balance with 1.4 and 22 kg $CO_2$ equivalents being saved depending on yields, production methods and the land cover prior to sweet sorghum cultivation (Köppen et al., 2009).

### 9.2 Crop description

Sweet sorghum is a specific type of sorghum that accumulates high levels of sugar in the stalk. It belongs to C4 crops.

#### 9.2.1 Growth stage of sweet sorghum

According to Vanderlip (1972) growth stages of sorghum can be divided into 3 main phases; vegetative, reproductive and grain filling. The vegetative phase is the period beginning from emergence, root growth, seedling development and establishment and leaf growth development or about 0-30 day after sowing for 90 d in sorghum. The reproductive phase is characterized by the differentiation of growing point into a floral merristem or inflorescence development and fertilizer, at approximately at 30-60 days after sowing. About 6-10 days before flowering sorghum will form as a bulge in the sheath of the flag leaf. Generally under warm climate, sorghum flowers in 55 to 70 days over 4-5 days. The grain filling phase is determined by the development and physiological maturity of grain. It takes 30 days beginning from the first ovule development to reach physiological maturity (House, 1985).

#### 9.2.2 Morphology of sweet sorghum

Roots of sweet sorghum are adventitious with numerous branched lateral roots (Doggett, 1988). The primary roots develop from radical first appear at germination. Secondary roots develop from the first node and develop into an extensive root system. The primary roots subsequently die. The brace root may appear later on the lowest nodes (House, 1985). Roots are found to increase until grain filling and decline toward maturity (Zartman and Woyewodzic, 1979). In grain sorghum, the silica located in the endodermis of roots strengthens the root to withstand drought conditions (Doggett, 1970) and aerenchyma development in the root cortex makes it tolerant to waterlogging conditions (Orchard et al. 1985).

The stalk of sweet sorghum is generally taller than grain sorghum. Height of sorghum is constituted of a sequence of nodes, ranging 0.8 – 5.0 m and a diameter of 1 to 5 cm (Grassi, 2001). Height also depends on internode length, peduncle length and panicle length and varies with genotypes (Doggett, 1970).

Sugar is accumulated mostly in the stalk with only 2% in the leaves and panicle. The central part of stalk has the highest sugar, followed by the base part and lowest in the apical part of the stalk (Jansen et al., 1930; Massacci et al., 1996). Before anthesis, vegetative growth is the preferential sink of assimilates. Sugar accumulates in the stem after anthesis (McBee and Miller, 1982) and reaches maximum 30 d after anthesis (hard dough stage) (Eastin, 1972; Massacci et al., 1996; Chavan et al., 2009). In the field experiment, sweet sorghum could maintain their sucrose content about one month after reaching the hard dough stage (Coleman, 1970; Broadhead, 1972a). There is no competition between grain development and sugar accumulation in the stalk (Lingle, 1987). At physiological maturity stage, sweet sorghum stems of dry matter of cv. Keller contain 31% sucrose, 7.53% glucose and 5.7% fructose under normal inputs (Ammaducci et al., 2004). On each node of the stem of sorghum, there is a single bud. On the lowest node, this bud may develop tillers or prop roots (Doggett, 1970). Tiller is important for stalk yield in syrup sorghum (Coleman, 1970). In general, tiller is more extensively developed during and after of the main shoot development (Isbell and Morgan, 1982).

Leaves of sorghum are similar to corn leaves but narrower. Sweet sorghum leaves have a dull midrib due to the presence of juice in the air space of the pitting tissues, which is different from grain sorghum (Martin et al., 1975). In general, leaf numbers are 14 - 17 leaves. They are dark green and developed at the node. The mature leaf length is usually about 30 to 135 cm and a width of 1.5 to 13 cm (Doggett, 1988). Stomata are located on both faces of leaves. There are several bulliform cells near the midrib on the upper side of the leaf. During drought stress, these cells result in a longitudinal rolling of leaves that reduces transpiration and leaf wilting (Stoskopf, 1985). Sweet sorghum leaf surface is about half that of corn. Together with the extensive root system, sweet sorghum possesses high resistance to drought.

The panicle (inflorescence) length of sweet sorghum varies from 2 to 70 cm with a diameter of 2 to 30 cm. One panicle produces up to 4,000 grains (Grassi, 2001). Seeds of sorghum reach physiological maturity at 25 to 55 days after flowering in tropical zone and 34 to 70 days in the temperate. The hilum usually turns dark (Eastin et al., 1973). In general, sweet sorghum had lower grain and panicle weight than common and fibre sorghum. Amaducci et al. (2004) reported that panicle of sweet sorghum had only 2% of biomass, compared to 28% in long cycle fibre sorghum. Sweet sorghum grains are frequently spheric and of very different colours, varying from light brown to black. Grain yield normally ranges between 1.5 to 5.5 ton $ha^{-1}$ in USA (Schaffert and Gourley, 1982) and between 2.67 to 7.19 t $ha^{-1}$ in India (Reddy et al., 2007c).

### 9. 3 Factors affecting sweet sorghum growth, yield and quality

#### 9.3.1 Cultivar

According to the type of sugar in the stalk, sweet sorghum can be divided in to saccharin-type and syrup type (Schaffert and Gourley, 1982). Saccharin- type sweet sorghum, which mainly contains sucrose, can be refined into crystal sugar. Syrup-type sweet sorghum, which mainly contains glucose, can be used for producing syrup. As both sucrose and invert sugars are directly fermentable, both types of sweet sorghum are equally suitable for ethanol production (Schaffert and Gourley, 1982). The desirable characteristics of both sweet sorghums include their ability to produce high yields per area, strong erect growth, high percentage of extractable juice, high juice quality, resistance to drought and waterlogging, comparatively short growing period, resistance to damage from insecticides and herbicides, seeds that germinate well and produce vigorous seedlings and adapt well to a wide range of soil and climatic conditions (Coleman, 1970). Schaffert and Gourley (1982) indicated that specific characteristics of sweet sorghum favorable for ethanol production should also include relatively low fertilizer requirements and production of grain for food and feed use as well as the possibility of complete mechanization.

According to Ferraris and Stewart (1979), there are early maturating and late maturating varieties. Early maturity varieties mature from 82 – 124 d after emergence, whereas late maturity varieties typically mature within 135-145 d from emergence. Late maturing varieties usually have higher yield of stalk per area than the early ones (Coleman, 1970). High sugar yield can be obtained from late maturing, tall and thick stalk cultivars with a relatively small grain yield but large leaf area on the stem (Ferraris, 1981a). Reddy et al. (2007a) also reported that tall and long-duration genotypes tend to produce more cane yield and juice volume with high Brix value. Breeding programs have been initiated to develop high–yielding cultivars specifically for bio-ethanol and bio-energy production, with emphasis on early maturity, non-photoperiodic and thermal cultivars for year round harvesting, disease and insect resistance, high energy sweet sorghum and stress tolerance for growing in the marginal lands.

There are readily available sweet sorghum cultivars in many growing areas. In USA and Brazil, cv. Wray is one of the most promising varieties for both commercial use and breeding programs due to its superior Brix value (19.3 compare to 16.4 in Brandes or 16.4 in Rio cultivar) (Schaffert and Gourley, 1982) and the highest stalk yield and sucrose content stability (Hills et al., 1990). Keller is also reported to be the highest potential cultivar in the USA due to its recorded total sugar yield across locations (Smith and Buxton, 1993). In India, SSV 74 produce highest cane yield, 72.4 t $ha^{-1}$ and 17.2 % Brix value, resulting in 5.5 t sugar $ha^{-1}$ (Reddy et al., 2007a), followed by new hybrid genotypes ICSR 165 (with 72.8 t can $ha^{-1}$, 17.7 % Brix and 4.8 t sugar $ha^{-1}$. In Beijing, China, recorded biomass yield with high total sugar yield is in late maturity Lvneng-3 hybrid line (Zhao et al., 2009). In Thailand, KKU 40, which has been developed from Keller cultivar, and Wray have record stalk yield and sugar content, ranging 20-26.25 t $ha^{-1}$ and 11.68%-14.67% Brix values, respectively. Cultivars reported as having high potential for ethanol production include KKU 40, Keller, Cowley and BJ248 (Jaisil and Sanitchon, 2006).

### 9.3.2 Cultural practices

***(i) Land selection and preparation*:** Sweet sorghum can grow well on latitude 40° N-S. Because it requires relatively high temperatures, it is suitable for tropical and sub-tropical regions. However, it can be grown as a summer crop in temperate climates i.e. USA (Smith et al., 1987; Smith and Buxton, 1993), Northern China (Zhao et al., 2009). Sweet sorghum grows well on a variety of soil from heavy clay to light sandy soils but the most favorable for growth and yield is loams and sandy loams. It can grow within a pH rage of 5.0-8.5 (Smith and Frederiksen, 2000). It tolerates some degree of salinity (Almodares et al., 2008b), alkalinity and poor drainage (Doggett, 1970; Almodares et al., 2008a). The average growing temperature is between 20-35 °C (Doggett, 1988). The optimum germination temperature is 23 °C (Kanemasu et al., 1975). Soil temperature over 45 °C inhibits seedling emergence, resulting in poor crop stand (Peacock, 1982).

Land preparation is similar to that used for grain sorghum. When the soil is adequately wet, land should be ploughed and harrowed to reduce the soil clod as well as control weeds. Well prepared seedbed will provide a favorable environment for rapid germination and establishment. Seed of sweet sorghum should be planted deep enough to ensure moisture for germination and allow the roots to grow down through soil moisture at deeper soil layers before soil surfaces become dry (Almodares et al., 2008a).

***(ii) Planting date:*** Generally, most sweet sorghum is a short day photoperiod sensitive plant (Ferraris and Stewart, 1979). This is the problem in tropical or sub-tropical regions to arrange for the supply of sweet sorghum stalks to the distilleries all round the year as well as to achieve the maximum stalk yield throughout the world. Generally, early planting is often reported for the recorded stalk yield, whereas juice quality is still controversial. In the USA, sweet sorghum stalk yield increases with an early planting date, while Brix value, sucrose content and juice purity were not affected by planting date (Hipp et al., 1969; Broadhead, 1972b; Cowley and Smith, 1972). In Iran, high plant height and diameter, fresh stalk yield, total dry weight, Brix value, sugar content and grain yield is also obtained at early planting date (Almodares et al., 1994; Almodares and Darany, 2006). In India, early planting date increases plant height (2.8 m), stalk weight (41.2 t $ha^{-1}$) and juice volume (12.4 kl $ha^{-1}$) but late planting has highest Brix value (18.1% compared to 12.3% of early planting date) (Reddy et al., 2007b). In Thailand, a similar response is found as in India but with higher plant growth and yield. Early planting (30 June) increased plant height (313 cm), population, fresh weight stalk (39 t $ha^{-1}$) and juice volume, while Brix value increases at late planting (Jaisil and Sanitchon, 2002). Under rainfed conditions Jaisil and Sanitchon (2007) reported that the optimum planting date was during early- and mid-planting in rainy season, giving 21-51 t $ha^{-1}$ of stalk yield, 12-20% Brix value, 1.38-2.41 cm in stem diameter and 260-354 cm plant height. In Botswana, early planting increases stalk yield through increased number of tillers and main stem height but reduces sucrose percentage and purity of juice (Balole, 2001). Decreased growth and yield at late planting is reported due to a reduction of growth period in sweet sorghum (Inman-Bamber, 1980) by reducing the growing period from emergence to panicle initiation and booting stage (Balole (2001) and by decrease in solar radiation received by plants (Hipp et al., 1969). Late planting may also cause late and troublesome harvest or expose the crop to dominant and hazardous pests and diseases (Almodares et al., 2008a).

***(iii) Plant density:*** In general, growing sweet sorghum too close planting space results in thin stems which lodge easily and produce less syrup per ton of cane, whereas too wide spacing provides too few stem per area, leading to low stalk and syrup yield (Doggett, 1970). Broadhead et al. (1963) reported that in one meter row, intra-row spacing wider than 15-20 cm decreased yields of stalk and syrup per hectare, while closer spacing than 15-20 cm resulted in lower stalk yield and juice extraction as well as thin stem. They recommended that populations ranging from 46,000 to 65,000 $ha^{-1}$ were optimum for stalk yield and juice quality. In Turkey, the row spacing at 65 cm and 5-10 cm intra-row spacing is recommended for 83 t $ha^{-1}$of forage yield, 30 t $ha^{-1}$ of dry matter yield (Turgut et al., 2005). In Botswana, 90 cm inter-row spacing with various intra-row spacing from 20 cm, 40 cm, and 60 cm has shown no significant effect on juice quality, while decreased spacing to 20 cm resulted in thin stem and vice versus for 60 cm spacing (Balole, 2001). However, Amaducci et al. (2004) found the increase in percentage of sucrose on the dry matter of stem when plant density was increased from 10 plants to 20 plants per $m^{-2}$. In Thailand the maximum stalk yield (26.25 t $ha^{-1}$) is obtained at 50 x 10 cm spacing, while plant spacing has no effect on Brix value (Jaisil and Snitchon, 2002).

***(iv) Fertilizer and irrigation management:*** In sweet sorghum fertilizer application should be done under adequate moisture conditions and at particular growth stages. It is recommended that fertilizer should be applied at planting to promote early growth. Late application of fertilizer rich in nitrogen may interfere with juice quality (Ferraris and Stewart, 1979). Sweet sorghum response to fertilizer depends on soil fertility. In USA, stalk and sucrose yield did not respond to different N fertilizer levels (Smith and Buxton, 1992). However, basal application of 18 kg N $ha^{-1}$

and 1 top dressing of 46 kg N $ha^{-1}$ were sufficient to obtain maximum sugar yield at maturity of sweet sorghum grown on low N and P content soil in India (Reddy et al., 2008). Sweet sorghum stalk yield increases with increased nitrogen application up to 120 kg N $ha^{-1}$ (Kumar et al., 2008) or 200 kg N $ha^{-1}$ (Turgut et al., 2005), but not for Brix value (Ferraris, 1981; Kumar et al., 2008). However, combination of N and K application increases yield of sorghum rather than application of N alone (Polsen and Sornsungnoen, 2004) due to the requirement of K for transformation of solar energy to chemical energy (Mengel and Kirkby, 2001). Almodares et al. (2008c) found an increase in stalk fresh weight, total sugar, sucrose content and juice extraction when applied 50 kg K $ha^{-1}$.

Even though sweet sorghum is a drought tolerant crop, having low water requirement, 8000 $m^3$ over 2 crop season compared to 36,000 $m^3$ in sugarcane (Reddy et al., 2007c), sorghum subjected to water deficit generally stops growing. It is reported that effective irrigation management results in higher plant height (>3.5 m), LAI (>6) and fresh stalk yield (148 t $ha^{-1}$) (Sakellariou-Makrantonaki et al., 2007). It is reported that irrigation should be done at early growth stage of sweet sorghum (Mastrorilli et al., 1999).

***(v) Weed control:*** Thinning should be done as early as possible before the young plant begins tillering, generally at 7-10 cm height. The first weed control should be done at the same time of thinning and it should be done several times to keep the field clean throughout growing season (Doggett, 1970) or until the closure of crop canopy (Cowley, 1969). Even though sorghum is sensitive of herbicide (Martin et al., 1975), pre-emergence application of atrazine at the rate of 3 kg $ha^{-1}$ (Inman-Bamber, 1980) or propazine at the rate of 2.2-3.6 kg $ha^{-1}$(Freeman et al., 1973) is an effective weed control. Post-emergence application of atrazine, bendioxide and bromfenoxin is also reported (Coleman, 1972; Inman-Bamber, 1980). In Thailand, two times hand weeding at 3 and 6 weeks after seeding resulted in recorded stalk yield (28 t $ha^{-1}$) and applications of pre-emergence of atrazine at the rate of 1 kg $ha^{-1}$, metolachlor at the rate of 1.5 kg $ha^{-1}$ and the mixture of both herbicide could be effective weed control in sweet sorghum production during rainy season (Promchum et al., 2003).

***(vi) Pest and disease control:*** Sweet sorghum is damaged by various kinds of insects and diseases, directly related to growth and yield or quality of juice. However, in Thailand there are no serious disease and insect problems. The observed pests for sweet sorghum are shoot fly (*Atherigona soccata*), aphids, *Mythimna separate* and *Helicaverpa armigera*, (Jaisil, 1986; Jaisil et al., 2006). Stalk borers (*Busseola fusca*) infestation can be great enough to destroy a crop for syrup production by causing stalk breakage (Coleman, 1970). African pink borers (*Sesamia calamistis*), causing shoot holes in the whole leaf or tunneling up in to the stem, sugarcane borer (*Diatraea sacharalis*), sorghum midge (*Stenodiplosis sorghicola*), armyworms (*Spodoptera frugiperda*) and wireworm (*Heteroderes spp.*) were also reported as the important insects in USA (Colman, 1970) and India (Murty et al., 1994).

Anthracnose and red rot, caused by *Colletotrichum graminicolum*, resulting in leaf damage and stalk breakdown, were reported as the most important disease that can decrease stalk yield and syrup production in many growing regions. This can be prevented by using resistant cultivars i.e. Brandes and Wray (Schaffert and Gourley, 1982). Other important stalk diseases are charcoal rot (*Macrophomina phaseolina*), which is the main disease in drying areas and fusarium rot (*Fusarium moniliforme*), which caused the internodes plants redish in pith and brown to red bundles and cause premature plant death (Murty et al., 1994). Ergot (*Sphacelia sorghi*) and kernel smut, which prevent and cause poor grain development, were also reported (Murty et al., 1994).

***(vii) Harvesting:*** Harvesting of the sweet sorghum at the proper stage of maturity is the most crucial for high stalk yield and high-quality syrup. The best harvest time for sweet sorghum occurred when the soluble carbohydrate content is at its highest level (Ferraris, 1981b). The maturity period of sweet sorghum plants depends on the varieties and the climatic conditions and varies considerably between years. Bitzer and Fox (2000) indicated that the crop should be harvested when the sugar was approximately in the range of 15.5-16.5 of Brix value. In USA, Broadhead (1972b) reported that highest sucrose content of sweet sorghum juice was between soft dough and ripe grain stages. In Iran, Almodares, et al (2006) found the highest stalk yield, Brix value, and sucrose content at physiological stage. In Thailand, the harvesting stage of sweet sorghum began from 20 days after 50% flowering (Jaisil and Sanitchon, 2002). Sugar content in the stem of sweet sorghum declines after ripening. It was reported that delayed harvesting after plant reach physiological maturity significantly reduce juice extraction, Brix value, total sugar content, but the values varied depending on cultivars. Broadhead (1969) recommended that there were no differences in stalk yield and juice quality when stems were harvested at 2 weeks after ripening or at ripening stage. At harvest, stalks are cut at soil level and leaf, leaf sheath and panicle may be removed depending on equipment used.

After harvesting, storage of stalk significantly affected sugar content and the extent of changes varied with cultivar. Broadhead (1969) found that stem of cv. Rio could be stored outdoors up to 2 days without change in sucrose content. However, Hansen and Ferraris (1985) found that in cv. Wray within the first 48 h, sucrose decreased from 34 to 19% of the dry matter. It was recommended that stalk sweet sorghum should be processed within 24 hours. On the other hand, it is reported that stalk weight decreased over time of storage but Brix values, reducing sugar and total sugar content increased (Jaisil and Sanitchon, 2002; Chavan et al., 2009).

**10. Sweet sorghum production under multiple cropping systems**

For grain sorghum, intercropping of sorghum with several crops in the upland areas has been done in India and some countries in Africa, where sorghum is the main source for carbohydrates (ICRISAT, 1981). Sorghum can be grown with cowpea, millet, maize, pigeonpea, sweet potato, roselle, groundnut, soya and cotton (ICRISAT, 1981; Willey et al, 1982). Ratoon cropping systems (Willey et al., 1982) and sequential cropping system with sorghum have also been reported (Rao, 1975).

In paddy fields, sorghum was grown after rice in the Philippines (Hooper et al., 1975), Bangladesh (Salahuddin, 1977). In Thailand, an experiment trying to use sorghum as a pre-rice crop in upper paddy field has been tested, however, the results were not promising because the long growing period of sorghum delayed rice transplanting and reduced rice yield (KKU-FORD, 1979). Growing sorghum as a rotation crop, particularly using sorghum as a primary crop, has been reported to depress yields of the following crops. The causes of yield reduction were the depletion of nutrients, moisture, the locking up of available nitrogen by microbial action in decomposition of carbon-rich stubbles and alleopathic exudates from sorghum stubble. Doggett (1970) concluded that the presence of toxic substances was not a major problem. The depressions of yield of following crops were primarily caused by nitrate depletion and moisture depletion.

Sweet sorghum based cropping system has been reported in many parts of the world. In Zimbabwe, Wood (2000) showed that sweet sorghum could be introduced into sugarcane fields during the fallow period. Sweet sorghum could be processed in existing sugarcane processing facilities and produces 46 t $ha^{-1}$ of fresh weight stalk, 3,000 l $ha^{-1}$ of ethanol and 12.6 GJ electricity from bagasse. In Louisiana, Thomas et al. (2008) reported that during fallow period, sorghum would need to be harvested no later than 120 DAP so as not to interfere with the planting of sugarcane in these fields. Sweet sorghum cv. Theis and cv. MMR 333/47, which produced theoretically sugar and fibre based ethanol 11,000 l $ha^{-1}$ with in 119 DAP are recommended. In China, late maturity sweet sorghum intercropping with short stalk and early maturity crops i.e. potato, sweet potato and pea has proven successful (Nan et al., 1994).

However, there are several factors to be taken into account for successful integration of sweet sorghum into existing cropping systems. These include available land and length of cropping system, primary crop species or cultivars, crop management, planting date, minimum biomass quality and quantity of both sweet sorghum and primary crop, market of the products, impact of new technologies introduced, government policies and perception or acceptability of the stakeholder including farmers, millers etc.