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Strategies for nitrogen fertilization of cotton (*Gossypium hirsutum* L.). A review

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Abstract

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The purpose of this review was to summarize the results obtained in Bulgaria and other countries on the impact of mineral fertilization on cotton yield. All authors confirm that a significant increase in seed-cotton yield was achieved by both using new varieties and through optimal fertilization. Nitrogen as a nutrient is of great importance for cotton productivity. Nitrogen fertilization leads to stronger increase in leaf area, dry matter accumulation, boll size and number of bolls. Accumulated nitrogen mainly depends on formed dry matter. At low nitrogen rates yield increased at higher phosphorus level. Suppressant effect of high nitrogen rates on growth and development is emphasized in richer soil and under excessive moisture when maturity is delayed. A number of authors have found genotypic specificity of cotton yield as dependent on fertilization rate.

Keywords: cotton; nitrogen fertilization; dry matter; yield
Abbreviations: N – nitrogen, P – phosphorus, K – potassium

Introduction

Cotton is one of the most important crops in the world and in Bulgaria, in particular, especially cultivated for fiber and oil seeds production (Ali, 2015). The main product is fiber, which is distinguished from artificial and synthetic fibers by its softness, electroneutrality and hygroscopicity. The cotton seeds are rich in protein and fat (17-27%), and are one of the alternatives to extraction of vegetable oils, including biodiesel.

Australia and Egypt produce the highest quality cotton fiber. China is the largest producer and largest importer of cotton in the world. On world markets, cotton occupies over 50% of the textile fibers, which is an indication of its economic importance. From the European Union member states, cotton is produced only in Greece, Spain and a small part in Bulgaria.

Cotton in Bulgaria is grown in the lowland areas of southern Bulgaria, where the temperature sum for the May-October period is above 3600°C, including Haskovo, Stara Zagora, Sliven, Yambol, Bourgas, Plovdiv and Blagoevgrad regions. Cotton can also be sown on soils polluted with heavy metals on which food crops cannot be grown. In recent years, the sown areas have increased compared to 2010 due to an increase in the purchase price and the introduction of additional subsidies and amounted to about 12,000 ha.

Meteorological data show that over the past 30 years the rainfall for the cotton growing season (May-October) has declined by 26% compared to the previous 63-year period (1928-1990). Climate change positively affects the warmth-loving cotton, which effectively uses the larger temperature resources and has a longer vegetation period. Through its deep root system, cotton productively uses the moisture in the two-meter soil layer.

The temperature sum and precipitations during the growing season of cotton under Bulgarian conditions is a limiting factor for the yield and quality of fiber. Higher productive and quality varieties have a longer growing period and under the country›s conditions they cannot mature in some years, especially with high nitrogen fertilization. The same applies to foreign varieties that do not ripen and give low or unstable yields per year, and do not form its quality indicators of fiber.

The impact of weather conditions on yield is of utmost importance because Bulgaria is on the northern border for cotton growing. Below (1995) points out that the effective use of fertilizers limit the impact of unfavorable weather conditions. According to Pettigrew (2008) by increasing the air temperature by 1°C, the fiber yield is reduced by 10%, and at too high temperatures the bolls mass and the seeds number per one boll are significantly reduced.

Under the influence of specific conditions and growing technology in Bulgaria, cotton forms less biomass, a lower bush, and has a shorter vegetation period compared to cotton growing in Greece and Spain.

The purpose of this review is to summarize the results obtained in Bulgaria and in other countries regarding the effect of nitrogen fertilization on cotton yield.

Influence of nitrogen fertilization on seed-cotton yield, fiber yield, earliness and yield components

Deficiency of nutrients and poor field management practices have imposed huge challenges on cotton growers to increase cotton yield and fiber quality (Dong et al., 2010). Fertilizer with proper management practices is one of the most important key factors to enhance cotton yield (Ali et al., 2007). Nitrogen is the main nutrient that affects growth, formation of fruiting elements and yield productivity (Paschalidis et al., 1994; Geriketal, 1998; Boquet & Breitenbeck, 2000; Shriram & Prasad, 2001; Paschalidis et al., 2002; Fritschietal., 2003; McConnell et al., 2003). N is needed continuously and in larger quantities than other nutrients for cotton production (Hou et al., 2007). N fertilization has a significant impact on plant growth, yield and fiber quality (Bondada et al., 1996, Boquet et al., 1993). It is an essential element for photosynthesis of cotton plants (Wullschleger & Oosterhuis, 1990). N is an important nutrient which controls growth and prevents abscission of squares and bolls, essential for photosynthetic activity (Reddy et al., 1996) and stimulates the mobilization and accumulation of metabolites in newly developed bolls and thus their number and weight are increased.

According to Girma et al. (2007), N, P and K have a significant influence on cotton yields, with N being decisive for all studied varieties, while phosphorus has a modest effect. The nutrients deficiency in cotton (*Gossypium hirsutum* L.) reduces total seed-cotton yield, fiber and seed yield, and fiber formation and development worsen (Panayotova, 2002; Clement-Bailey & Gwathmey, 2007; Kolev et al., 2008; Sawan, 2008). Cotton yield varies widely depending on the environmental conditions, fertilization, soil tilth, crop rotation, variety, etc. (Wesley et al., 2001; Panayotova, 2002; Saldzhiev et al., 2005; Clement-Bailey & Gwathmey, 2007; Sawan, 2008; Coker et al., 2009). Ali et al. (2007) also indicated that cotton yield can only be improved by proper management practices, the most important of which are levels of fertilization and crop density.

N fertilization leads to higher cotton yield and also increases nutrient supply both in soil and in plants (Halevy et al., 1987; Paschalidis et al., 1994; 2002; Panayotova, 2009). The year conditions impact took the largest part of the total variance, forming both seed-cotton yield and lint yield (Panayotova & Genov, 2004; Panayotova, G. 2008). The N rates affect greatly plant height, boll weight and 1000 seeds weight, except fibre length. N fertilization has moderate influence on total seed cotton and lint yield, and minimum on lint percentage and earliness, manifested in September yield. The cultivar led to the largest significant differences in fibre length, lint percentage, 1000 seeds weight, September and lint yield. Its influence on bolls per plant was low, while the cultivars were not significantly different in respect to boll weight and plant height. The September yield, number of bolls and height of plants were the most unstable. Some authors (Hu et al., 2006; Zhang & Zhang, 2010; Mohsen & Rashidi, 2011) point out that nitrogen deficiency leads to lower fiber quality. Seilsepour & Rashidi (2011) reported that N application significantly increased boll number, boll-weight, seed cotton weight per boll, seed cotton yield and lint yield.

Plant nutrition using a balanced fertilization with both macro- and micronutrients has become very important in the production of high quality seed. Many management practices and breeding efforts have allowed plants to partition more carbohydrates into bolls and less into vegetative growth. Mineral nutritional status of plants has a considerable impact on partitioning of carbohydrates and dry matter between shoots and roots. Often, the number of sink organs is the yield component that is affected mostly by mineral nutrients. The positive effect of nitrogen supply on the number of sink organs may be a result not only from an increase in mineral nutrient supply, but also from an increase in photosynthate supply to the sink sites or from hormonal effects (Borowski, 2001). With cotton, N has the most necessity role in production inputs, which controls growth and prevents abscission of squares and bolls, essential for photosynthetic activity (Reddy et al., 1996) and stimulates the mobilization and accumulation of metabolites in newly developed bolls, thus increasing their number and weight.

Luo et al. (2019) reported that cotton producers have substantially reduced their inputs (labor, nutrients, and management) mainly by adopting a short season cropping management that is characterized by late sowing, high density, and reduced fertilization with one-time application at the first bloom stage without lint yield reduction. The results suggest that one-time fertilizer application at the first flower stage might be an adjustment that is more effective and economic management practice than at first bloom, and allow for easier decision making for application date as no counting of plants with flowers is needed.

Considerable research has shown that an increase in bolls on the middle fruit branches and internal parts resulted in increased cotton yield, but these studies have focused on water and fertilizer application (Zhang et al., 2003; Clawson et al., 2006; Read et al., 2006; Dai et al., 2015).

The optimal density of cotton crops also depends on the N level and other agronomic practices (Zhang et al., 2011). The study of the effect of plant density and N fertilization on the source-assimilation ratio in relation to early aging of the leaves helps to clarify the influence of plant populations and N level on yields and yield components. It has been found that the plant density and N nutrition are a strong influence on the growth and yield of cotton plants, and their individual effects are well documented (Bednarz et al., 2000, Bednarz et al., 2005). The highest lint yield is achieved by a high N dose at low plant density, but comparable yields are achieved at moderate and low N rates and medium and high plant density levels. It was found that increased plant density and N rate decrease the number of formed bolls, which is negatively related to the photosynthesis of the leaves in the late season. The delayed leaf aging due to high plant density is mainly due to reduced load of bolls and possibly increased nutrition and reduced bolls loading due to the increased N rate (Rinehardt et al., 2004; Boquet, 2005; Ali et al., 2007). A higher lint yield is due to the increased weight of the bolls. Authors indicate that early aging of leaves in late stages has a significantly negative effect on cotton yield and yield components (Wright, 1999; Dong et al., 2006). Early leaf aging may arise from the poor ability of cotton plants to absorb nutrients from the soil in the late season, or from the imbalance between applied fertilization and uptake.

Sowing is a critical time in the life cycle of any crop and the seeds are frequently exposed to adverse conditions that may compromise the establishment of seedlings in the field (de Figueiredo e Albuquerque, 2003). The weight and number of mothers' seeds as well as nutrients in the seeds are determined by the nutrient soil reserves during flowering and boll formation (Fenner, 1992). Seed weight significantly increased by adding the high N-rate. This may be partially due to enhanced photosynthetic activity (Abdel-Malak et al., 1997). Similar findings were obtained by Gil and González (1997). Sawan & Ioio (2016) reported that seed quality is one of the most important factors for stand establishment in cotton (*Gossypium* sp.), and the use of good quality seeds is therefore essential to obtain an optimum plant population.

Cotton-seed quality is affected, to a large extent, by the indeterminated growth habit of the cotton plant, which allows seed to set and develop across an extended period of time. Both size and number of seeds, produced by maternal plants, are most likely determined by their nutritional status at the time of flowering and bud initiation (Welch, 1995). Furthermore, the most important single determinant of mineral nutrient reserves in seeds is the mineral nutrient availability to the maternal plant during reproductive development, with increasing supplies of a particular mineral nutrient enhancing the nutrient concentration in the mature seed (Fenner, 1992).

The N utilization is closely linked to phosphorus nutrition. P deficiency impairs N nutrition (Sawan et al., 2008). The application of N, P and K fertilizers has a positive effect on yield, as a large part of the influence due to N and P is of secondary importance. (Girma et al., 2007). Phosphorus significantly increases the yield, nitrogen uptake, chlorophyll content and dry matter (Sawan et al., 2008). Results of long-term precision studies in Bulgaria show that N fertilization increases the seedcotton yield by 30% on average and P – up to 18% (Panayotova, 1999). Panayotova (2004) states that NP and NPK fertilizers, imported pre-sowing and combined with additional nitrogen feeding or foliar spraying have the best effect on cotton plants. For the conditions of Bulgaria it has been found that at moderate N and P soil reserves the fertilization $N_{120-160}P_{80-120}$ is optimal, whereas the total yield exceeds the unfertilized by 11.5-32.0% depending on the conditions of the years, the September yield is on average 13.0% higher, lint yield exceeds by 12.3%, boll weight by 3.5%, number of bolls per plant by 9.8%. In the case of irrigation, the fertilizer utilization rate is increased and higher fertilizer rates are applied. The concentration of N in the leaves as an indicator of N status is useful for optimizing the management of N in cotton.

Genotype specificity of cotton related to nutrition level

According to some authors, cotton varieties have specific requirements to fertilization (Fritschi et al., 2003; McConnell et al, 2003; Karamanidis et al., 2004; Clement-Bailey & Gwathmey, 2007), while others (Pettigrew et al., 1996; Kostadinova & Panayotova, 2003; Ivanov, 2004) reported that the differences in the effect of nutrition on cultivars with similar origin are negligible. Genotype specificity of cotton to the nutrients absorption was established by Meredith & Wells (1989), but Mullins & Burmester (1990) reported that the concentration and uptake of macronutrients were not proven as influenced by the variety.

Bulgarian varieties have similar requirements to the level of nutrition, but the optimization of fertilization for different varieties is good production practice for obtaining optimal economic results (Panayotova, 2002).

Rate of nitrogen fertilization

High yield potential cannot be realized without optimal amounts of nitrogen nutrition in the soil during the different stages of development (Kirchmann & Thorvaldsson, 2000; Stavrinos et al., 2002). The application of optimal rates for cotton production varies depending on soil type, productivity, climate and various other factors for soil and crop management (Christidis, 1985; Gericetal., 1998; Boquet & Breitenbeck, 2000; Boquet, 2005). However, the nitrogen rate for maximum profitable yield depends on the price of N fertilizer and the market price of the harvest (Wajid et al., 2007; Baraich et al., 2012).

Due to chemical changes that affect N as its mobility, leaching, denitrification and evaporation, it is difficult to estimate precisely the amount of the fertilizer rate, and the soil should be analyzed for mineral nitrogen content. Therefore, errors made in N management that can impact the crop can be through either deficiencies or excesses. With a dynamic crop like cotton, excess N serves to delay maturity, promote vegetative tendencies, and usually results in lower yields (McConnell et al., 1996; Rinehardt et al., 2004). If an N deficiency is developing in a cotton crop, it is not particularly difficult to diagnose and correct. Excess N fertility levels, which can be damaging to final crop productivity, are subtler to detect, and are difficult to correct (Silvertooth & Norton, 1997).

Nitrogen should be applied fractionally, which usually results in a higher NUE, applying 1/3 to 1/2 pre-sowing, and the rest is imported through the bud formation-flowering. The optimum input of nitrogen is an important factor to enhance N use efficiency which enhances cotton yield.

Recommendations for fertilizer rates range from very low to very high (Clawson et al., 2008). Shriram & Prasad (2001) found that the application of N 80 kg.ha^{-1} leads to maximum values of cotton plant height, leaf area and leaf index, dry matter, nitrogen uptake and cotton seed yield.

According to Yang et al. (2011) the conventional average nitrogen rate in China is 300 kg/ha. A number of other studies have also focused on the influence of a balanced optimal N rate on cotton yield and yield components (Boquet et al., 1993; Boquet & Breitenbeck, 2000; Bondada & Oosterhuis, 2001; Clawson et al., 2008). Gil and González (1997) applied N at a rate ranging from 40 to 200 kg ha^{-1} to cotton plants and found that the highest yield was associated with high rates of applied N. Similar results were obtained by Sarwar et al. (2009) and Saleem et al. (2010) when N was applied at 120 kg.ha^{-1}.

Recently, increasing fertilizer costs and increasing attention to greenhouse gas emissions has led to greater attention to the effective use of N fertilizers (Rochester et al., 2007). These issues and the need to optimize nitrogen input according to crop requirements are increasingly identified as priorities for cotton growers and consultants. Rochester et al. (2009) reported that over N 50 kg.ha^{-1} was applied to cotton fields in Australia and 15-25% of the applied N fertilizers could be reduced without reducing the yield. Dong et al. (2010) also suggest that N fertilizers can be used at a moderately lower rate and more effectively than traditionally used.

The optimal N rate is not defined, it is clear that the optimal N levels and use efficiency are influenced by various factors like yield potential, soil fertility and field management (Chen et al., 2010; Dong et al., 2010). Managing N nutrition in cotton is difficult due to problems with excessive or inadequate levels, the influence of other agronomic practices (density, chemical control) as well as abiotic stress factors (drought, salinity) (Rinehardt et al., 2004). Deficient N levels from emergence to early flowering may result to inadequate vegetative growth, which leads to a reduction in fruit bolls (Gardner & Tucker, 1967). N deficiency throughout the growing season reduces the number of bolls due to poor plant growth and premature aging (Zhang et al., 2011). Conversely, overdose N will promote excessive vegetative growth and delayed maturity (Hodges, 2002). According to Sawan et al. (1998) seed yield/plant and yield/ha significantly increased by raising the N rate. Abdel-Malak et al. (1997) stated that cotton yield was higher when N was applied at a rate of 190 kg.ha^{-1} than at the rate of 143 kg.ha^{-1}. Seilsepour & Rashidi (2011) reported that cotton yield was obtained in case of 200 kg.ha^{-1} N application rate and this application rate resulted in 19.6% increased seed cotton yield and this application resulted in the highest boll number, boll weight, seed cotton yield and lint yield. For example, the production of cotton increased up to high limit when the rate of nitrogen application was kept at 300 kg.ha^{-1} (Wang et al., 2010). In certain other research, maximum lint production was attained in Nanjing at the moderate rate of 240 kg.ha^{-1} and 300 to 360 kg.ha^{-1} in Anyang (Li et al., 2010).

In many areas in Bulgaria and abroad N fertilization with a positive balance is applied. This leads to the irrational N use from fertilizers and accumulation of nitrate N in the soil layer, while at the same time it is a prerequisite for groundwater contamination (Stavrinos e al., 2002). In recent years a critical review of the use of high fertilizer rates has been made for more effective use of N in cotton. Plants cannot absorb the excess N in the soil, this unused N is slowly washed out of the soil through the water runoff, resulting in groundwater and drinking water being polluted with nitrates (Clawson, 2008).

According to Munir et al. (2015), the rows spacing and N rate can significantly affect earliness and seed-cotton yield (*G. hirsutum* L.). These two agrotechnical factors significantly influence plant height, number of internodes on the stem, number of plant bolls, boll weight, and seed yield per unit area. Earliness increases with lower N norms (60 kg.ha^{-1}). High yield of cotton seeds is obtained by application of N180 kg.ha^{-1}, which is not statistically proven against N120 kg.ha^{-1}. The authors conclude that in order to achieve optimal seed yield, the cotton should be grown at 75 cm rows spacing and fertilization of N120 kg.ha^{-1}. Raphael at al. (2019) also report that the earliness of yield decreases at fertilization with high N levels due to later formed and late ripened bolls at the top fruit sites.

The studies have shown that both N deficit and excessive use have a negative impact on plant growth and total yield. N deficiency reduces the yield, number of bolls, leaf area and total biomass (Huet al., 2006; Zhang & Zhang, 2010; Mohsen & Rashidi, 2011). Excessive N use activates vegetative growth by formation of larger leaves with a greater possibility for photosynthesis, and thus the energy for reproductive growth is redirected to the vegetative mass. Plants may not even form the necessary reproductive organs in case of enhanced vegetative growth (Mozaffari et al., 2004).

Time of nitrogen fertilization

Typically, the addition of N fertilization in three different period corresponds to the stages of plant growth, with best application before sowing, in bud-formation and in full flowering. In Bulgaria, cotton is grown mainly under non-irrigation conditions and nitrogen fertilization is carried out pre-sowing, with sowing and during the budding stage. Corrective nutrition during vegetation with complex foliar fertilizers is a good agricultural practice.

Pre-sowing and sowing N fertilization provides sufficient time for nitrogen to become an inavailable form, but in this case there are higher risks of N losses, especially at low temperatures or heavy rain (Hallikeri & Gershenzon, 2006). At the beginning of the growing season, young plants do not require too much N, and the incorporated N into the soil is subjected to washing by rain for more than 60 days, before the absorption reaches its maximum. Very high N levels in the beginning of vegetation can lead to excessive vegetative growth and delayed maturation. The second application period is about 45-50 days after emergence at the beginning of the flowering stage, and the absorption of nutrients accelerates. The maximum removal is reached about two weeks after the first flowering, when the flowers are formed and the bolls begin to grow. It is possible the second feeding after two weeks of first flowering, to provide N to ripening, but this high late N values can cause excessive vegetative growth. Such late feeding should only be applied on soils with low N reserves and under irrigation conditions. Soil and plant analysis in the most important stages of cotton development, as well as other management decisions, such as the N level, time and type of fertilizer, should be taken into account to correct N rate, improve NUE and reduce production costs. The time of N fertilization has a strong impact on NUE.

Nitrogen uptake of cotton

N uptake is directly related to the formed biomass and the concentration of N in the plants and is determined by the food stocks as well as by the weather and soil conditions.

According to Ali et al. (2003) N uptake can be as much as 230 kg ha^{-1} and N removal at harvest can be as much as half of the total uptake. The high yield of cotton is closely associated with the uptake of NPK nutrients (Saleem et al., 2010). Marschner (1995) states that export of N decreases at phosphorus deficiency.

With regard to cotton fertilization, it has been established that for formation of 100 kg of seed-cotton yield, together with the respective additional production in Central South Bulgaria under non-irrigated conditions the uptake is 3.4-5.0 kg N, 1.2-1.5 kg P_2O_5, 3.0- 3.8 kg K_2O, and for 100 kg fiber – 0.93-2.0 kg, 0.27-0.44 and 0.90-1.34 kg, respectively, depending on soil supply and applied fertilizers (Panayotova, 2004).The effect of 1 kg N, P and K is 2.52-4.0 kg, 0.51-0.85 kg and 0.54-0.6 kg seed-cotton, respectively. The increase of fertilizer level leads to increase in N uptake per 100 kg cotton, but the effect of 1 kg N and efficiency of utilization decrease.

Globally, the interest of researchers and farmers to more effective genotypes to nitrogen and phosphorus (Ortiz-Monasterio et al., 2001; Guarda et al., 2004; Hirel et al., 2007) and creating cultivation strategies for higher efficiency of N use increases (Foulkes et al., 2009).

Boquet & Breitenbeck (2000) indicate that the study on N status in cotton areas leads to better N efficiency, optimizes crop development and yield, and excessive N fertilization can be avoided. For cotton the maximum N uptake was determined to be between 49 and 71 days after germination and was 2.9 and 4.3 kg/ha/day, respectively at 84 and 168

N kg.ha^{-1} fertilization. At maturity, the plants uptake N160 kg.ha^{-1} with aerial biomass and an additional N50 kg.ha^{-1} in plant residues at fertilization with N84 kg.ha^{-1}, which is N111 kg.ha^{-1} more than without N fertilization. It has been proven that N content in the subtending leaf of a boll is closely related to its growth and fiber development, are significantly enhanced with appropriate inputs of the sufficient N fertilizer (Ma et al., 2009).

According to Xu et al. (2012) and Tang et al. (2012), cotton accumulates approximately N 250-300 kg.ha^{-1} in order to achieve maximum yield, and uses less than half of the N fertilizer applied during the same season, receiving most of the N from the soil instead of the N fertilizer. It was found that on average 33% of fertilizer N is absorbed, 25% remains in the soil at maturity, and the rest (approximately 42%) is lost from the system.

Conclusions

The issue of cotton fertilization is relevant for achieving high and stable yields, for sustainable economic growth of farms, for maintaining agricultural land in good condition. The nitrogen nutrition is an important factor for increasing the quantity and quality of cotton production.

Analysis of the cited sources and obtained results concerning different aspects of cotton fertilization and nutrition allows us to conclude that the published opposing views of the issues under consideration are due primarily to the different conditions under which the studies were carried out and to the biological characteristics of the tested varieties.

Obtaining new knowledge of yield responsiveness to changes in the presence of assimilates during different periods of vegetation, determining the parameters for effective uptake, use and utilization of nitrogen is important for establishing agronomic, physiological and agrochemical parameters suitable for good complex evaluation of the cultivated cotton genotypes.

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