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学 位 の 種 類	博士（農学）
学 位 記 番 号	甲第３６１号
学位授与年月日	平成１７年　３月１５日
学位授与の要件	学位規則第４条第１項該当
学 位 論 文 題 目	Genotypic Responses of Growth, Yield and Quality of Bread Wheat to High Temperatures during Various Growth Stages（コムギにおける異なる生育ステージの高温に対する生長、収量および品質の遺伝子型反応）
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学 位 論 文 の 内 容 の 要 旨

Wheat has the broadest adaptation of all cereals and more land is devoted to its production worldwide than to any other commercial crop. The continuously increasing demand for wheat resulted in its expansion to environments that are regarded as marginal because of heat, drought and soil problems. Heat stress is a problem in 40% of the wheat areas in the temperate environments, while over 7 million ha of wheat are grown under continual heat-stressed environments of arid and semiarid areas. The central clay plain of the Sudan is atypical example of the hot, irrigated and low humidity environments of wheat production. The development of heat-tolerant wheat cultivars capable of producing good yield and acceptable grain quality is crucial for the successful production of wheat in these environments. This study investigates:

1- The effects of high temperature on grain yield and quality and the differential responses of wheat genotypes grown in a hot irrigated environment.

2- Selection criteria associated with yield under a hot irrigated environment that could accelerate the development of heat-tolerant wheat cultivars.

3- The capability of different bread wheat genotypes to remobilize nitrogen (N) and total non-structural carbohydrates (TNC) stored in their stems under heat stress conditions and the association of N and TNC remobilization efficiency with grain yield and its components.

4- The effects of high soil and high air/soil temperatures during early and grain filling stages on wheat growth, grain yield and related traits and their differential responses to such stress.

Several experiments were carried out to fulfill the above-mentioned objectives.

1- Genotypic and temperature effects on grain yield and quality

Fifteen wheat genotypes in 2000/01 and 18 genotypes in 2002/03 were grown under optimum and late sowing conditions of the hot irrigated environment of the Gezira Research Farm, Wad Medani, Sudan. High temperature significantly decreased grain yield by decreasing grain weight. Genotypes responded to late heat stress by increasing protein contents, SDS sedimentation volume (SDSV), mixograph peak height (PH) and the descending slope at 2 min past peak (DS). In contrast, mixograph peak time (PT) and the curve width at 2 min past peak (CW) were significantly decreased. Genotypes varied in magnitude of response of most quality parameters to high temperature during grain filling. Grain yield and weight were negatively correlated with most of the quality parameters. Flour protein correlated positively with SDSV, PH and DS and negatively with CW. PT correlated negatively with DS and positively with CW. Results indicate that high temperature increased protein content, SDSV and PH and hence the gluten strength, but decreased flour mixing time and tolerance and hence the dough elasticity. Grain quality could be improved under high temperature conditions utilizing the available variability; however, it might require evaluations under various growing conditions.

2- Potential selection criteria under early and late heat stresses

This study was conducted for two seasons at the Gezira Research Farm, Wad Medani, Sudan, using ten wheat genotypes and three sowing dates (early, optimum and late). Grain yield of the three sowing dates significantly correlated with biomass, grains m^{-2}, spikes m^{-2}, grain growth rate, biomass growth rate and vegetative growth rate. In addition, the early sowing grain yield significantly correlated with grains $spike^{-1}$ while that of the late sowing correlated with harvest index, thousand grain weight and grain filling duration. Similar correlations were also found between the heat stress intensity of yield and most of the counterpart traits in the early and late sowings. These results suggest biomass, grains m^{-2}, spikes m^{-2} and vegetative growth rate as selection criteria under early heat stress. Harvest index, thousand grain weight and grain growth rate could be used as selection criteria under late heat stress.

3- Remobilization of nitrogen and carbohydrate in response to heat stress

Eighteen genotypes were used for N remobilization study while nine of them were used for TNC remobilization study. Five days after anthesis (5DAA), half of the plants were taken to phytotrons where temperature was gradually increased and the maximum was set at 38 °C while the other half were left in a vinyl house kept below 30 °C. Significant differences were found among genotypes in percent reduction in grain yield (GY), grain weight (GW), grain filling duration (GFD) and harvest index (HI) due to heat stress. Heat stress significantly reduced the N remobilization efficiency (NRE) of most of genotypes; while it has significantly increased TNC remobilization efficiency (TNCRE) and significant variation were observed among genotypes. NRE across treatments significantly correlated with GY, GW, HI and GFD. TNC at 5DAA negatively correlated with N at 5DAA and HI, but the TNCRE under heat stress positively correlated with mainstem GY, GW and HI. The rate of chlorophyll loss from flag leaf positively correlated with NRE and TNCRE under heat stress suggesting a link between leaf senescence and remobilization efficiency. Results indicate that heat stress negatively affected GY, its components and N remobilization while it increased TNC remobilization due to the increasing demand for resources.

4- Responses of wheat genotypes to high air and soil temperatures

Three genotypes, Imam, Fang and Siete Cerros were grown under three temperature treatments during early and grain filling stages. The temperature treatments during early stages were: (i) normal air/normal soil temperature (22/22°C), (ii) normal air/high soil temperature (22/38°C) and (iii) high air/high soil temperature (38/38°C) and during grain filling were: (i) 26/26°C, (ii) 26/38°C and (iii) 38/38°C.

During the early stages, high root (22/38 °C) and shoot/root (38/38 °C) temperatures significantly decreased Photosystem II quantum yield (Φ_{PSII}), photosynthetic rate (A_n), specific leaf area and root growth of the three genotypes compared with the control (22/22 °C). Leaf and shoot dry weight and leaf area plant^{-1} were significantly decreased by 38/38 °C treatment but remained unaffected by 22/38 °C treatment. The heat tolerant Fang always had the highest chlorophyll content (chl), Φ_{PSII} and A_n under all treatments conditions, while the heat sensitive Siete Cerros always had highest reduction in these traits especially towards the end of the experiment. Fang and Imam responded to 38/38 °C treatment by immediately and greatly reducing their shoot and root growth while Siete Cerros was the least affected during the first week of the treatment. The situation was reversed with the duration of the treatment such that Siete Cerros was the most affected genotypes towards the end of the experiment. It is concluded that wheat genotypes differentially responded and adapted to 38/38 °C treatment by reducing leaf weight and area and hence accumulating more chl in the diminished leaves. The failure to undergo such changes under 22/38 °C treatment led to lower chl, Φ_{PSII} and A_n.

During the grain filling stage, the 26/38 °C and 38/38 °C treatments significantly decreased chl, GFD and increased carbohydrate remobilization or loss from the stem and the root, but with varying degrees among genotypes. GY, biomass, GW, grains spike^{-1} and HI under 38/38 °C treatment were significantly lower than under the other two treatments. Imam showed lower GY under 26/38 °C than under 26/26 °C, while Siete Cerros showed lower GY, GW, grains spike^{-1} and HI under 38/38°C treatment. The results indicated that high soil temperature alone or together with high air temperature decreased chl and GFD and increased carbohydrate remobilization. Differential genotypic response to both high temperatures was found suggesting the existence of variability among wheat genotypes in this respect.

It is concluded that high temperatures at various growth stages studied here significantly affected the growth, yield and quality of wheat. Immense genotypic variations were found in their responses to high air and soil temperatures. Some selection criteria were identified at various growth stages. The effective use of these selection criteria could greatly enhance the development of heat-tolerant genotypes with high yields and good grain quality under similar high temperature conditions.

論 文 審 査 の 結 果 の 要 旨

コムギは従来冷涼な気候のもとで栽培され，栽培面積は広い適応性により穀作物中世界最大である。コムギ栽培は消費量の増加に伴い，高温，乾燥などコムギにとって劣悪な環境の地域にまで拡大した。スーダン中部でも高温，乾燥下でコムギの潅漑栽培がされ，そのような環境での継続的生産には，良質多収の耐暑性の高いコムギ品種の育成が必要不可欠である。本論文では（1）高温乾燥下で潅漑栽培されたコムギの収量および品質に及ぼす高温の影響，（2）耐暑性コムギ品種育成のための選抜指標の探索，（3）熱ストレス下での稈貯蔵の窒素および非構造炭水化物の再移動，（4）収量および収量構成要素に及ぼす高地温および高地温と高気温との相互作用，について検討した。

1. 高温乾燥下で潅漑栽培されたコムギの収量および品質に及ぼす高温の影響

スーダンの Wad Medani で 2000/01 に 15 品種を，2002/03 に 18 品種を供試し，適期播種栽培と登熟期が高温である晩播栽培を行った結果，登熟期の高温は品質を高めるが，収量を減少させ，その反応程度に品種間差異が認められたことにより，高温の登熟期でも一定量の収量が得られる良質品種の育成は可能であることを明らかにした。

2. 耐暑性コムギ品種育成のための選抜指標の探索

コムギ品種 10 品種をスーダン，Wad Madani で適期，早期，晩期に播種し，生育初期の高温

ストレス耐性に関する選抜指標としてバイオマス，単位面積当たりの粒数，穂数および栄養生長速度が，また，登熟期の高温ストレス耐性に関する選抜指標として収穫指数，千粒重，種子登熟速度がそれぞれ有効であることを明らかにした。

3. 熱ストレス下での稈貯蔵の窒素および非構造炭水化物の再移動

窒素（N）の再移動に関して18品種，非構造炭水化物（TNC）の再移動に関して9品種をそれぞれ供試した。供試材料をポット栽培し，開花後5日目に最高温度30℃以下のビニルハウスと最高温度 38℃の自然光人工気象箱に分けて搬入し，温度処理を行った。収量，粒重，登熟期間，収穫指数は高温処理により全供試品種で減少したが，減少程度に品種間差異が認められた。N再移動効率は多くの品種で熱ストレスを低下し，収量，粒重。収穫指数，種子登熟期間との間に有意な正の相関を示した。一方，TNC再移動効率は熱ストレス下で上昇し，その上昇程度に品種間差異が存在した。なお，熱ストレス下でのTNC再移動効率は主稈の収量，粒重，収穫指数との間に正の相関を示した。

熱ストレス下での止葉のクロロフィルの消失割合がNおよびTNC再移動効率との間に正の相関が認められ，再移動効率は葉の老化と関連あることを示唆した。熱ストレスは収量，収量構成要素およびN再移動効率に抑制的に作用するが，ソースとしての必要性からTNC再移動効率を高める作用をすることが明らかとなった。すなわち，コムギの耐暑性品種では熱ストレス下での種子登熟のために，稈貯蔵TNCを効率的に主稈の穂に移動させることを明らかにした。

4. 収量および収量構成要素に及ぼす高地温および高地温と高気温との相互作用

耐暑性の異なるコムギ品種 Imam, Fang および Siete Cerros の3品種を用いて，栄養生長期，登熟期にそれぞれ地下部と地上部の温度を組み合わせた温度処理を行い，生育に及ぼす影響を検討した。

栄養生長期には気温と地温の組合せが 22/22℃，22/38℃および 38/38℃の3条件で処理を行った結果，22/38℃と 38/38℃処理は全供試品種において対照の 22/22℃区に比べ光化学系Ⅱ光量子収量（Φ_{PSII}），光合成速度，標準葉面積，根の生長を減少させた。地上部乾物重および葉面積は 38/38℃処理では減少したが，22/38℃処理では影響を受けなかった。耐暑性品種である Fang および Imam は葉重，葉面積を減少し，特定の葉にクロロフィルを集積することにより地上部，地下部の高温に反応し順化したが，Siete Cerros は高温に反応できず，地下部のみの高温下でもクロロフィル含量，Φ_{PSII}，光合成速度の低下が生じ，生育が抑制された。

登熟期の 26/26℃，26/38℃，38/38℃の温度処理では，26/38℃および 38/38℃処理はクロロフィル含量，登熟期間を減少させ，炭水化物の再移動すなわち稈や根の炭水化物の消失を増加させたが，その程度に品種間差異が存在した。38/38℃区の収量，バイオマス，粒数，収穫指数は他の処理区より有意に低かった。Imam は地下部の温度が高い 26/38℃区で収量が 26/26℃区より低下した。Siete Cerros は 38/38℃区で収量，粒重，粒数，収穫指数が有意に低下した。これらの結果は，高地温が単独または高気温との相互作用でコムギのクロロフィル含量，登熟期間を減少させ，炭水化物の再移動を増加させることを明らかにした。

以上のように，本論文は圃場条件，制御条件下での地温，気温の熱ストレスに対するコムギの

反応における品種間差異を明らかに，コムギの耐暑性育種における選抜に関する貴重な基礎資料を提供するものであり，学位論文として価値あるものとして判定した。