Breeding crops for nutrient use efficiency

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(2018 – 11 – 175)

MSc. Plant Breeding and Genetics

Seminar report

Submitted in partial fulfilment of requirement of the course

GP 591, Seminar (0+1)

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DECLARATION

I, Abdul Basir (2018 – 11 – 175) hereby declare that the seminar report titled 'Breeding crops for nutrient use efficiency' has been completed by me independently after going through the references cited here and I haven't copied from any of the fellow students or previous seminar reports.

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CERTIFICATE

This is to certify that seminar report titled ‘Breeding crops for nutrient use efficiency’ for the course GP 591, has been solely prepared by Abdul Basir (2018 - 11 - 175) under my guidance, and he has not copied from seminar reports of seniors, juniors or fellow students.

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1. Introduction

In modern agriculture, sustaining crop yields are the main objective. So, agricultural production must increase to match the growing population. Hence, increased Nutrient Use Efficiency (NuUE) in crops have the most important role for sustainable agriculture. This has to be achieved with little further increase in the area of arable land and with limited and progressively expensive supplies of fertilizer. Greater productivity has to occur at a time when large areas of the world's agricultural land will experience increases in the frequency and severity of heat stress and drought improvements are also needed in the nutrient content of the most important stable food crops to alleviate the chronic nutritional problems that occur in many countries, but particularly in developing countries.

The past five decades have seen some remarkable changes and advances in crop production, from the Green Revolution in the early 1960s to the advent of modern biotechnology in the 1990s. Improved crop management and agronomy combined with improved crop genetics through conventional breeding and genetic engineering have been the major factors behind increased crop production. Crop genetic improvement has been responsible for 50% to 60% of the increases in crop yields and is still a crucial component of any strategy to increase crop yields and nutrient use efficiency. Additionally, large increase in yield has also been due to the use of synthetic nitrogen (N), phosphorous (P), and potassium (K) fertilizers. One example of high fertilizer uses and increased yields can be seen in the maize breeding programs, where breeders have selected for high seed-density-tolerant, high-yielding genotypes, in synchrony with high levels of applied N fertilizer.

2. Objectives

Improving crop nutrient efficiency can improve agricultural sustainability by increasing yield while decreasing input costs and harmful environmental effects. (Shen *et al.*,2012)

3. Definitions of nutrient use efficiency

Nutrient use efficiency has been usually defined in terms of crop yield (measured as biomass or grain produced) per unit fertilizer input or the achievement of an intended outcome with a lowest possible input of cost. (Hawkesford *et al.*,2016)

4. Estimation of NuUE in Plants

Partial factor productivity

$$\boxed{\text{PFP} = \frac{\text{Crop yield (Kg)}}{\text{Available N in soil + applied Nutrient (Kg)}}}$$

Agronomic efficiency

$$\boxed{\text{AE} = \frac{\text{Crop yield increase (Kg)}}{\text{Available N in soil + applied Nutrient (Kg)}}}$$

Apparent recovery efficiency

$$\boxed{\text{ARE} = \frac{\text{Nutrient taken(Kg)}}{\text{Available N in soil + applied Nutrient (Kg)}}}$$

5. Nutrient requirements for crop plant

Plants contain small amounts of 90 or more elements, but only 17 elements are known to be essential for plant growth.

Plant Essential Nutrients

Divided into two groups

Macronutrients

- Structural nutrients : C, H, O
- Primary nutrients : N, P, K
- Secondary nutrients : Ca, Mg, S

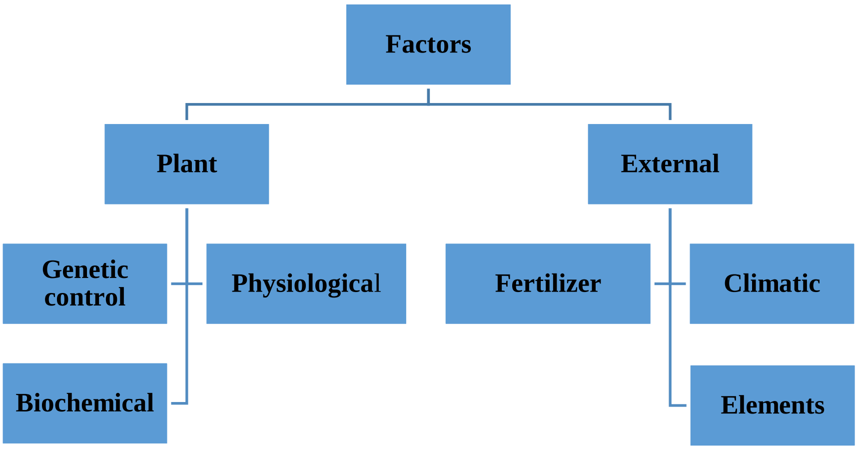
Micronutrients

- Fe, B, Cu, Cl, Mn, Mo, Zn, Co

Macronutrients: used in large quantities by the plant

Micronutrients: used in small quantities by the plant (Fageria *et al.*, 2005).

6. Factors affecting NuUE in Plants



- **Genetic control:** Species /cultivar/genotypes
- **Physiological**: Roots length, Root density, Root lateral and Root hair
- **Biochemical Enzymes:** nitrate reductase (N), phosphatase (P) Root exudate (citric, malic, trans aconitic acid)
- **Climatic** Adequate soil moisture Extreme temperature
- **Elements** Toxicities: acidic soil (Al, Mn and pH)
- **Fertilizer** Ammonification ion, nitrification inhibitors

(Baligar *et al*., 2001)

7. Breeding for Nutrient Use Efficiency

The case for breeding for better nutrient efficiency has been debated strongly in the past If breeding for improved NTUE is to be successful, a number of conditions need to be met: (a) there needs to be useful genetic variation in NTUE; (b) the genetic basis of the trait needs to be understood; and (c) appropriate selection criteria need to be defined, which often will require an understanding of the important physiological determinants of nutrient efficiency. There also needs to be no yield penalty associated with improvements in nutrient efficiency. (Roberts *et al*., 2008)

8. Genetic Variation in Nutrient Use Efficiency

Over the past 30 years, there has been a considerable amount of work that has characterized genetic variation in nutrient efficiency among the major food crops This has demonstrated that there are significant levels of genetic variation in nutrient efficiency among genotypes of staple food crops, which can be exploited in breeding programs. Despite this, progress in developing nutrient efficient crop.

9. Mechanisms of Nutrient Use Efficiency

Several reviews have described the mechanisms of efficiency for a number of nutrients. The strategies used by plants to promote uptake and enhance yield can be considered in terms of two fundamental processes.

- Ability to acquire nutrients from the soil.
- Efficiency with which nutrients taken up by plants are used to produce biomass and grain.

Mechanisms of nutrient acquisition include alterations to the chemical and biological properties of the rhizosphere to increase nutrient availability, increases in the volume of soil explored by increased root growth and changed root architecture, interactions with microbial populations in the rhizosphere, and changes in the expression of ion transporters in the roots to enhance uptake. Efficiency of utilization may include greater root to shoot translocation of nutrients, compartmentation of nutrients and partitioning within the plant, metabolic efficiencies and greater remobilization. The relative importance of different mechanisms is likely to vary with the severity of nutrient stress.

10.Approaches to improve nutrient use efficiency

10.1. Conventional

10.2. Molecular

10.1. Conventional

- Improving NuUE crops achieved through Directly or indirectly make a contribution to its superior ability to take up and/or utilize available nutrients
- Changes in one or more morpho-physiological traits of plants

10.1.1 Morphological factors related to nutrient use efficiency

- Root-length
- Root surface area
- Number and density of root hairs

Improving Nitrogen Use Efficiency and the availability of genetic variability:

Given the environmental heterogeneity that exists for nutrients in the soil, it is perhaps not surprising that there is a significant amount of genetic variation and phenotypic plasticity for NUE. Therefore, in addressing whether we can use traditional genetics to improve NUE, one needs to determine the level of genetic variation present in the different land races and genotypes of a crop. In order to parse out the contribution of N level from genetic and other environmental effects to plant yield, researchers need to be able to study a defined genetic population under different N conditions. However, as mentioned above, there are other factors to consider besides the genetics, such as the interactions between N uptake and water availability and the interaction between different macronutrients and micronutrients. When selecting for NUE, any variation in the environmental conditions could be as significant as genotype. If genotype rather than phenotype is used for selection, then an understanding of the genes that control the desired traits is also required.

A large genotype by environment (G×E) interaction on the expression of target traits is undesirable because it implies that the sought after improvements are not robust and may be observed only under specifically controlled conditions. In addition, the trade-offs associated with other desirable characteristics must also be considered. For example, modifying the root system to increase the uptake of nitrate from the subsoil could have negative effects on the uptake efficiency of less mobile, topsoil-located ions such as phosphate. In order to reconcile some of these conflicting demands and to help direct plant breeding, greater emphasis is currently being placed on the design of crop ideotypes for particular cropping systems and end uses.

Genetic improvement in NUE of crops may be achieved through changes in one or more morpho-physiological traits of plants, which directly or indirectly contribute to its superior ability to take up and/or utilize available N.

Wheat (irrigated) - 50% of the yield gains were associated with higher nitrogen uptake efficiency and the other 50% with better utilization efficiency. (Ortiz-Monasterio *et al.*, 1997). A clear understanding of the specific root traits (weight, length, or density) that are important for superior nitrogen uptake efficiency is require to identify nitrogen use efficient genotype (Anbessa and Juskiw, 2012).

10.1.2. Case Study

Green Super Rice developed with nitrogen use efficiency

Material and Methods:

- BC_1F_2 population
- (Recepient) WRT-1 x Hao-An-Nong (Donar)
- Six levels of nutrient inputs (NPK, 75N, -N, -P, -NP, and -NPK

Seeds of the 230 ILs , parents, and four checks used:

No	Checks	Traits
1	PSB Rc82	Low input tolerant and irrigated
2	NSIC Rc222	High yielding irrigated
3	Apo	Rainfed drought tolerant
4	IR74371-70-1-1	Rainfed drought tolerant

Table 1: Checks used in experiment

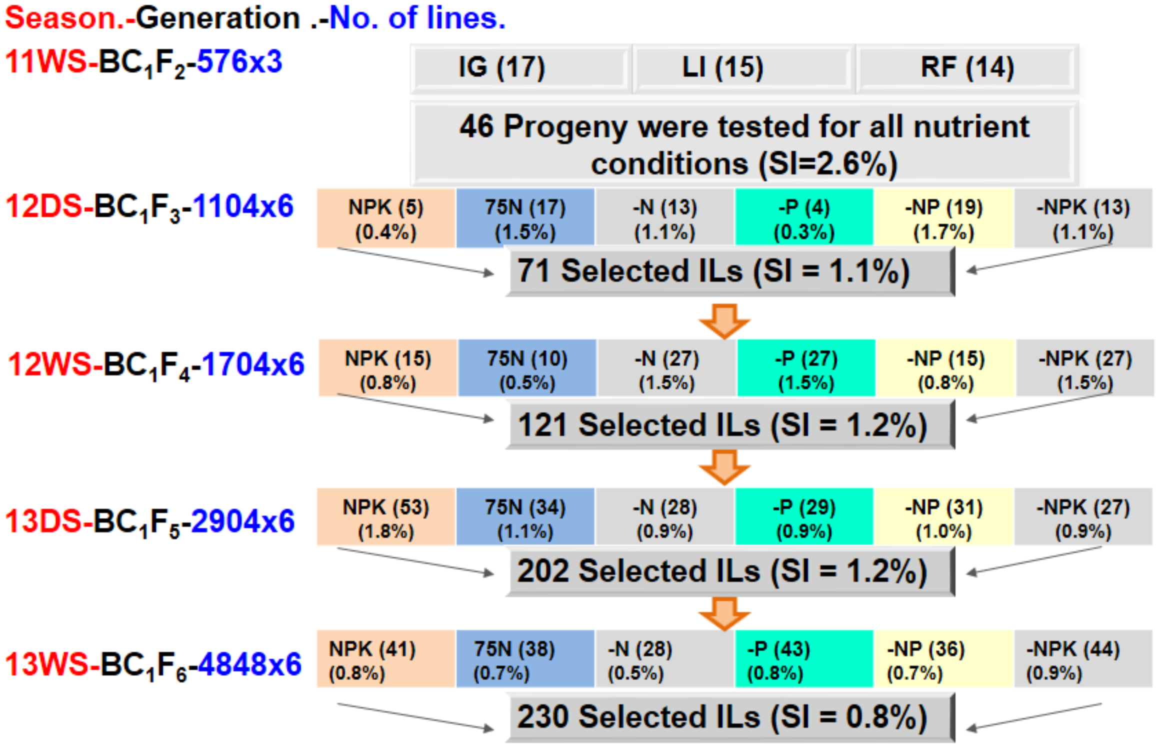


Fig 1: Phenotypic selection scheme for the identification of nutrient use efficient ILs under six nutrient conditions.

WTR-1, Weed Tolerant Rice 1 (recipient); HAN, Hao-An-Nong (donor); IG, irrigated conditions; LI, low-input conditions; RF, rainfed conditions; ILs, introgression lines; SI, selection intensity; Sea, season; Gen, generation; No. of lines, number of lines, grown under six nutrient conditions; DS, dry season; WS, wet season.

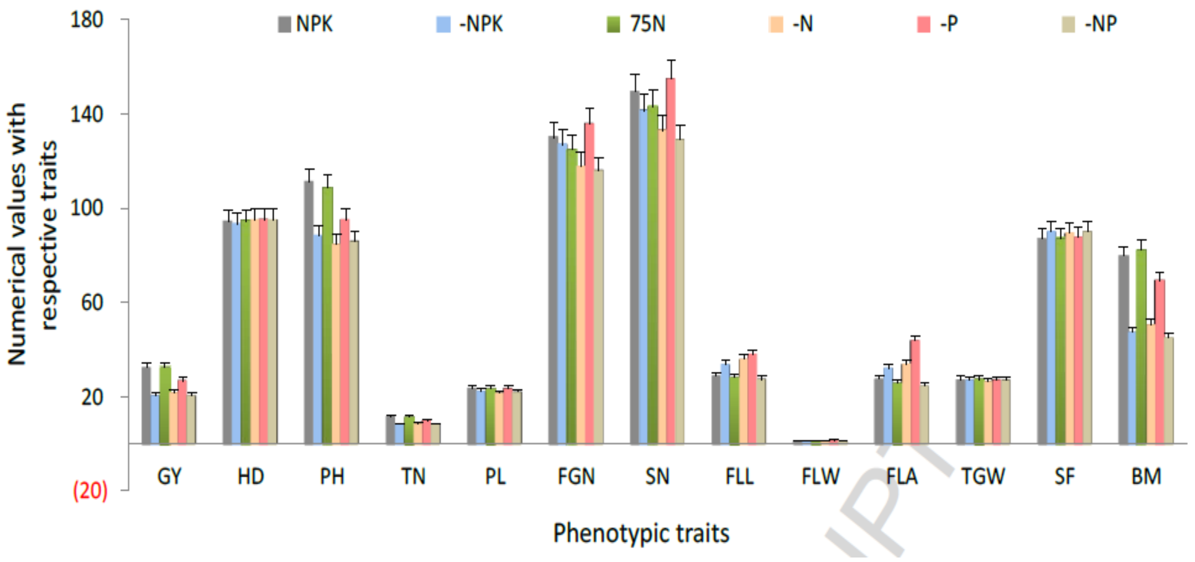


Fig: 2. Effects of nutrient conditions on the average expression of grain yield per plant (in g, GY) and related agro-morphological and yield-attributed traits of 230 WTR-1 introgression lines**.**

GY, grain yield per plant (g); HD, heading date (days); SN, spikelet number per panicle; FGN, filled grain number per panicle; SF, spikelet fertility (%); TGW, thousand-grain weight

S. No	ILs	Designation	NuUE Combinations					
			NPK	75N	-N	-NP	-NPK	-P
1	Nue-57	GSR IR2-1-L1-NU1-NU1-NU1-NU1	√	√	-	-	-	-
2	Nue-60	GSR IR2-1-RF6-NU3-NU4-NU68-NU35	-	√	-	-	-	√
3	Nue-77	GSR IR2-1-RF6-NU3-NU4-NU7-NU38	-	-	-	√	-	√
4	Nue-86	GSR IR2-1-RF6-NU4-NU7-NU60-NU56	-	-	-	√	-	√
5	Nue-106	GSR IR2-1-RF6-NU4-NU9-NU14-NU66	√	√	-	-	-	-
6	Nue-118	GSR IR2-1-RF6-NU6-NU1-NU20-NU88	√	-	√	-	-	-
7	Nue-228	GSR IR2-1-RF6-NU7-NU2-NU77-NU94	-	-	-	√	√	-
8	**Nue-112**	GSR IR2-1-RF6-NU7-NU2-NU76-NU96	√	-	-	√	√	-
9	**Nue-114**	GSR IR2-1-RF6-NU7-NU3-NU82-NU97	√	-	√	√	-	-
10	**Nue-229**	GSR IR2-1-RF6-NU7-NU2-NU37-NU100	-	√	-	√	√	-
11	**Nue-230**	GSR IR2-1-Y17-NU2-NU5-NU6-NU7	-	√	-	√	√	-
12	**Nue-115**	GSR IR2-1-Y17-NU2-NU5-NU6-NU8	-	-	√	√	√	√

Table 2: Twelve promising higher yielding ILs with superior yield performance in two or more nutrient conditions.

Result

Developed superior varieties with high and stable yield under rainfed condition and improved nutrient use efficiency (NuUE) 112,114, 115,229 and 230 (Jewel *et al.*,2019).

10.2. Molecular approach

10.2.1. QTL & Candidate gene detection

10.2.1.1. Case study

A genetic relationship between nitrogen use efficiency and seedling root traits in maize as revealed by QTL analysis.

Objective

To Uncover the most promising regions for MAS of RSA (Root System Architecture) to improve NUE in Maize.

Material and Methods

- RIL population- Ye478(NUE inbred) x Wu312 (NU inefficient inbred)
- Under high and low N conditions, 10 NUE and 9 RSA related traits – 4 field and 3 hydroponic environments respectively
- 184 and 147 QTLs- NUE and RSA related traits respectively and assigned into 64 clusters.
- 5 important QTL clusters at chromosomal regions bin1.04, 2.04,3.04,3.05/3.06 and 6.07/6.08 in QTLS favorable for both related traits from parents.

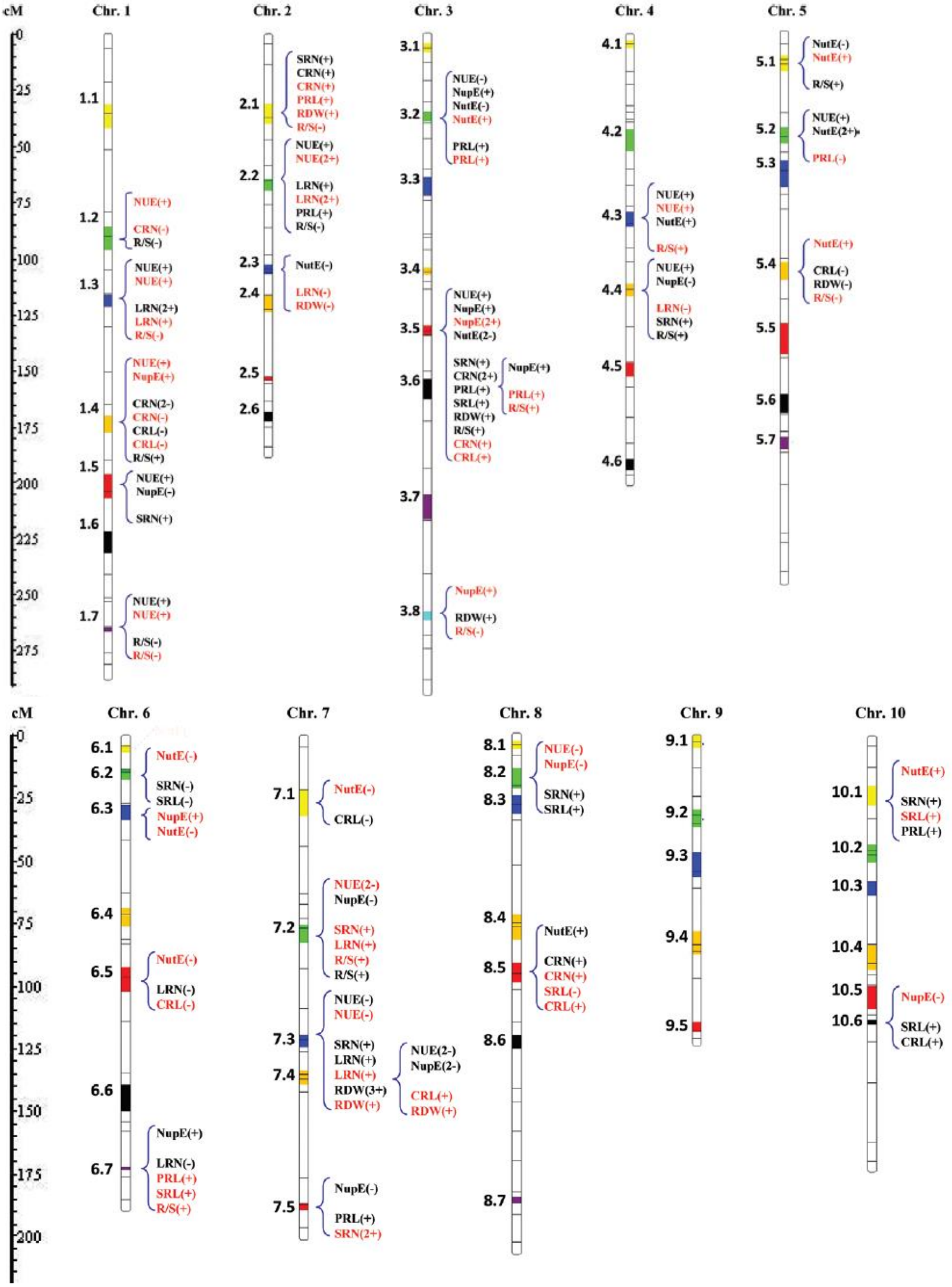


Fig: 3. Location of the QTL clusters detected for all investigated traits as revealed by meta-QTL analysis

Note: Relationship between RSA and NupE traits at QTL clusters may correspond to control of pleiotropic genes or to different closely linked genes.

Results

QTL clusters introgression- yield to ~ 14.8% for the line *per se* and ~15.9% in the test cross (Li *at el.*, 2015).

10.2.2 Transgenic approach

- Identification of the genes that affect nutrient efficiency
- Facilitate breeding of crops
- Tolerance to low-nutrient condition
- Improve fertilizer use efficiency improve crop yields
- Overexpression of N assimilatory genes and TF overexpression of a tobacco NR gene in wheat increased the seed protein content, without the need for increased N fertilization.

10.2.2.1. Case study

MicroRNA-targeted transcription factor gene RDD1 promotes nutrient ion uptake and accumulation in rice.

- Observed the function of the genes RDD1 which is responsible for nutrient uptake and accumulation in rice
- MicroRNA is a small non-coding RNA molecule found in plants, animals and some viruses,
- miRNAs function via base-pairing with complementary sequences within mRNA molecules

Material and Method

- Plants grown in hydroponic nutrient solution
- Low and high nutrient conditions
- Nutrients: $NH_4H_2PO_4$, KNO_3, $MgSO_4$, $CaCl_2$
- Seedlings were maintained and growth at 28°C under dark and light conditions

Observation

- Transgenic rice: Over expression of *RDD1*
- RDD1 induced genes associated with transport of NH_4^+, Na^+, SO_4^-, $PO3^-$
- Uptake and accumulation of sucrose and nutrient ion in low nutrient condition

Result

- RDD1 gene contributes increased nitrogen responsiveness
- RDD1 contributes to increased grain yield by inducing efficient uptake and accumulation of various nutrient ions (Iwamoto *at el.*, 2016).

11 List of genes used in transgenic approaches to improve NuUE

Nutrients		Gene/Qunatitative trait loci	Species	Reference
Various nutrient ions		RDD1	Rice	Iwamoto and Akemi, 2016
		GPC-B1 (NAM-B1)	Wheat	Hagenblad *et al.*, 2012
Macronutrient	N, P	miR169 (TaNFYA-B1)	Wheat	Qu *et al.*, 2015
	N	qNGR9	Rice	Sun *et al.*, 2014
		OsNPF8.20 (OsPTR9)	Rice	Léran *et al.*, 2014
		OsNRT2.1	Rice	Yan *et al.*, 2011
		OsNRT2.3b	Rice	Feng *et al.*, 2017
		OsAMT1;1	Rice	Ranathunge *et al.*, 2014
		TaNAC2-5A	Wheat	He *et al.*, 2015
	P	1BL/1RS 1AL/1RS 1DL/1RS	Wheat	Yediay *et al.*, 2010
Macronutrient	K	PSTOL1	Rice	Gamuyao *et al.*, 2012
		OsPHF1	Rice	Chen *et al.*, 2011
		OsPHR3	Rice	Guo *et al.*, 2015
Micronutrient	Fe	OsIRT1	Rice	Lee and An 2009
		OsYSL2	Rice	Ishimaru *et al.*, 2010

		ENOD12B:AtIRT1, AtNAS1, and PvFERRITIN	Rice	Chen, *et al.*, 2017

Table 3. List of genes used in transgenic approaches

12 Examples of improved NuUE varieties

Nutrient	Crop	Region	Reference
Nitrogen	Maize	Southern and eastern Africa	Ba¨nziger *et al.*,2006
Phosphorus	Soybean	China	Wang *et al.*,2010
	Wheat	China	Yan *et al.*, 2006
	Common bean	Mozambique	McClean *et al.*, 2011
Manganese	Barley	South Australia	Jennings, 2004
Iron	Soybean	USA	Wiersma, 2010

Table 4: Examples of improved NuUE varieties

13 Challenges

Despite exciting opportunities, there are some of challenges for improving nutrient use efficiency in plant , whether based upon conventional genetic or transgenic approaches.

- Breeding for improved NuUE is still in its infancy
- Lack of significant advances for development of molecular technologies.

14 Summary

- NuUE can improve agricultural sustainability
- Increasing yield while decreasing input costs
- Decreasing harmful environmental effects
- Breeding strategies can increase the ability to use native soil nutrients
- Breeding strategies can increase the ability to use native soil nutrients
- without altering the yield potential of the crop

15 Conclusion

- NuUE governed by multiple interacting genetic and breeding approaches.
- Researches had used different breeding strategies such as:
  - Conventional
  - Molecular

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DISCUSSIONS

1. Kappen (Department of Agronomy)

   Question: Why you have used different abbreviations? Example you have used NuUE for nutrient use efficiency but it was possible to use NUE.

   Answer: it's just for comparison between nitrogen use efficiency and nutrient use efficiency.

   NuUE = nutrient use efficiency

   NUE : nitrogen use efficiency

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COLLEGE OF HORTICULTURE, VELLANIKKARA
Department of Plant Breeding and Genetics

GP 591: Master's Seminar

Name	: Abdul Basir	Venue	: Seminar Hall
Admission No	: 2018-11-175	Date	: 13-12-2019
Major Advisor	: Dr. P. Sindhumole	Time	: 10.00 am

Breeding crops for nutrient use efficiency

Abstract

Agriculture is the mainstay of most of the developing countries across the globe and continues to play a major role in sustaining the population. The world population is expected to increase to 9.8 billion by 2050. United Nations Food and Agriculture Organization (FAO, 2017) predicts that the agriculture sector will need to produce 70 per cent more food to feed this extremely increasing population. One of the main problems in the development of economically effective agriculture is nutrient deficiency (Fageria and Baligar, 2005). Hence, improving crop nutrient use efficiency can improve agricultural sustainability by increasing yield while decreasing input costs and harmful environmental effects.

Nutrient use efficiency (NuUE) is a measure of how well plants use the available nutrients. It can be defined as yield (biomass) per unit nutrient input (Gaju *et al*., 2016). The mechanisms of nutrient use efficiency and breeding approach for improving NuUE features along with the role of regulation of gene expression in enhancing crop's nutrient use efficiency to increase yield. Conventional breeding, transgenic and molecular approaches are the important strategies for enhancing NuUE in crops.

Genetic improvement in NuUE of crops could be achieved through changes in one or more morpho-physiological traits of plants, which directly or indirectly contribute to its superior ability to take up and/or utilize available nutrients (Anbessa and Juskiw, 2012). Backcross (BC) breeding has been used for developing crops with improved nutrient use efficiency (Jewel *et al.,* 2019). Molecular approaches such as Quantitative Trait Locus (QTL) and transgenic have been used for NuUE.

A significant genetic relationship between Root System Architecture (RSA) and NUE traits by QTL analysis uncovered the most promising regions for Marker Assisted Selection of Root System Architecture (RSA) to improve NUE in Maize (Li *et al*., 2015).

Breeding approaches can increase the ability to use native soil nutrients without altering the yield potential of the crop. Despite exciting prospects, there are several challenges to improving NuUE, whether based upon conventional or transgenic approaches. Improvement of genes, transporters, and enzymes plays an immense role in enhancing nutrient use efficiency. However, the necessity in creating crops that require decreased nutrient levels has been recognized in the call for a second green revolution.

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