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PREFACE

Rice is a major food security crop for half of the world's population, particularly in East, South, and Southeast Asia. In terms of rice production, Asia is the leading producer, accounting for about 90 percent of the world's production, and it is of immense importance for the food security of Asian countries. Rice is also affected by various biotic and abiotic stress factors. Among the biotic factors, insect pests cause substantial damage to rice and threaten food security worldwide. Insect infestations are especially severe in rice, which grows in warm and humid environments. Rice plants provide an attractive and nutritious food source for many phytophagous insects. Among the insect pests, Brown planthopper attained the number one pest status in India in the last decade. It causes 40-70% yield loss, and severe infestation leads to 70-100% losses. Resistant varieties are the most suitable option for the management of Brown planthopper. The screening work conducted at ICAR-National Rice Research Institute, Cuttack, Odisha identified several resistant germplasms to BPH. Among these, "*Salkathi*" and "*Dhobanumberi*" are the landmark germplasm that revolutionized the host plant resistance research against brown planthopper in India. Breeders used these landraces and developed several resistant pre-breeding lines. From the landrace *Salkathi*, NRRI scientists identified two resistant QTLs (*qBph4.3* & *qBph4.4*). *Dhobanumberi* derived resistant CR line (CR2711-76) was used for identification of BPH resistance gene *BPH31*. These identified QTLs and genes were introgressed into popular rice varieties "Naveen" and "Tapaswini" – a evidence of remarkable journey from landraces to varieties. Besides, we are in the process of pyramiding both these QTLs and genes in the rice variety "Swarna" and "Pooja". The information generated here will encourage entomologists and plant breeders to identify the new resistant donors further and incorporate the reported genes and QTLs in the popular rice varieties of different states of India to solve the brown planthopper infestation in rice.

Authors

CONTENTS

1. Introduction

Rice is an essential food commodity grown in about 121 countries globally and serves as the staple food for more than half of the World's population. It is grown in over 117 countries and is the staple food of 3.9 billion people who depend on rice for their daily nutrition ((Lin et al., 2022). Furthermore, it is the agricultural commodity with the third-highest worldwide production, after sugarcane and maize. To meet the demand of an increasing population, 40% more rice needs to be grown by 2030 and 70% by 2050 (Khush, 2013). Insect pest are the major biotic constraint that causes substantial damage to agriculture and threatens food security worldwide (Oerke, 2006). Insect infestations are especially severe in rice, which grows in warm and humid environments. Rice plants provide an attractive and nutritious food source for many phytophagous insects. Hundreds of insect species damage rice to various degrees, but only ~ 20 species occur regularly and cause major damage to rice (Jena et al., 2018).

Several leafhoppers and planthoppers species assumed severe proportions in the rice crop in different parts of India (Jena et al., 2018). Amongst the different leafhoppers and planthoppers species, the brown planthopper, *Nilaparvata lugens* (Stal.) is regarded as the major phloem sucker insect-pest of rice, which is causing significant economic losses every year in tropical, sub-tropical as well as temperate regions of all rice growing areas in Asia (Jena et al., 2016; Pandi et al., 2018). The large number of nymphs and adults sucking the phloem sap from leaf sheaths and the basal portion of the rice plant. The hopper feeding interferes with the translocation of photosynthates from sources in leaves to sink in tiller buds or grains, thus affecting plant growth, development, and yield. The rice plant hoppers are common in rainfed and irrigated conditions. At the high population density of these pests, hopper burn or complete drying (Figure 1) of the

Figure 1. Rice field affected with brown planthopper showing “hopper burn” symptom

plants is observed, which may result in up to 40-70% yield loss (Min et al., 2014; Jena et al., 2018; Pandi et al., 2018). The infestation and hopper burn occurrence leads to severe yield losses up to the tune of 70-100% (Min et al., 2014; Jena et al., 2016; Pandi et al., 2018). Besides, BPH also acts as a vector for grassy stunt and ragged stunt viral diseases (Figure 2) of paddy plants (Cabauatan et al., 2009).

Figure 2. Rice field affected with brown planthopper showing viral disease symptom

1.1. Potential impact of BPH on rice production

Brown planthopper is a global rice pest that has occurrences in India, China, Bangladesh, Sri Lanka, Thailand, Vietnam, Malaysia, Korea, Japan, Indonesia, Philippines, Fiji, Papua New Guinea, and the Solomon Islands. Brown planthopper's first outbreak in India was recorded during the 1970s, but then it was mainly confined to Southern states. Later on, it got distributed to eastern states. Since the last decade, it has been occurring regularly in Odisha, West Bengal, Goa, Chhattisgarh, Bihar, Uttar Pradesh, Gujarat, Uttarakhand, Tripura, Maharashtra, Haryana, Punjab, Delhi, and Assam. In 1973, extensive damage to rice crops in Kerala (Pandi et al., 2017) was first observed, destroying about 50,000 hectares of rice (Bai et al., 2010). An estimated outbreak of this pest was reported in parts of the Cauvery Command Area in Karnataka in 2007; and in Haryana, Punjab and Delhi during 2008 and 2013 (Jena et al., 2018; Pandi et al., 2018). The last decade frequently witnessed BPH outbreaks in parts of Odisha, West Bengal, Chhattisgarh, Jharkhand, and Andhra Pradesh, resulting in major yield losses (Table 1) (Jena et al., 2006; Jena and Kim, 2010; Kumar et al., 2020). In 2017, an infested area in Bargarh district was assessed as about 37185 ha, consisting of partial and complete infestation.

Table 1. States affected by BPH outbreak in India

Year	Insidences of BPH in different states
2001	Andhra Pradesh, Punjab
2002	Andhra Pradesh, Punjab
2003	Tamil Nadu
2004	Tamil Nadu
2005	Odisha, Karnataka, Tamil Nadu
2006	Andhra Pradesh
2007	Haryana
2008	Haryana, Uttarakhand, Odisha
2009	Karnataka, Odisha
2010	Haryana, Maharashtra, Odisha, Puducherry, Punjab, Tamil Nadu, Bihar, Andhra Pradesh
2011	Maharashtra, Punjab, Himachal Pradesh, New Delhi, & Andhra Pradesh
2012	Nalgonda (Telangana), Hyderabad (Telangana), Ragolu (AP), Maruteru (AP), Moncompu (Kerala)

2013	Ludhiana (Punjab), IARI (New Delhi), Raipur (Chhattisgarh), Nalgonda (Telangana), Moncompu (Kerala), Pattambi (Kerala), Ragolu (AP), Wangbal (Manipur), Karaikal (TN)
2014	Cuttack, Bargarh (Odisha), Nalgonda, Warangal (Telangana), Maruteru, Ragolu (AP), Pattambi (Kerala), Aduthurai (TN), Jagdalpur (Chhattisgarh), Titabor (Assam).
2015	Sakoli (Maharashtra), Warangal, Rajendranagar (Telangana), Pantnagar (Uttarakhand), Pattambi, Moncompu (Kerala), Raipur (Chhattisgarh), Ragolu (AP),
2016	Panipat, Sonepat (Haryana), Samastipur, West Champaran and Vaisali (Bihar), Bargarh, Sambalpur, Ganjam (Odisha).
2017	Tekkali and Amudalavalasa (AP), Ludhiana and Fathehgarh Sahib (Punjab), Samba (Jammu & Kashmir), and Kanke (Jharkhand). Chhattisgarh, Odisha, Haryana, Karnataka, Kerala and Telangana
2018	Maharashtra, Chhattisgarh, Pondicherry, Tamil Nadu, Himachal Pradesh, Punjab, West Bengal
2019	Sirmour (Himachal Pradesh), Karnal (Haryana), Patiala (Punjab), Navasari (Gujarat), Pattambi (Kerala), Karaikal (Puducherry), Mysore, Mandya and Chamarajanagar (Karnataka), Telangana
2020	Odisha
2021	Punjab
2022	Kanchipuram (Tamil Nadu), Odisha
2023	Burdwan (West Bengal), Balasore (Odisha), Kerala

(Source: Production orientation survey and Pest survey report, ICAR-IIRR; NRRI Survey, Jena et al., 2022)

The brown planthopper caused substantial monetary losses. In Asia, the estimated losses due to BPH infestations are quite high, as much as $300 million annually (Min et al., 2014). For instance, in India, the losses have been estimated at around US $20-40 million (Dyck and Thomas, 1979; Kumar et al., 2019). Other countries like Indonesia and the Philippines have also reported significant losses, with figures reaching US $100 million and US $26 million, respectively (Dyck and Thomas, 1979; Liu et al., 2016). A severe infestation occurred in Southern Vietnam from 2005 to 2006, where more than 485,000 ha of rice fields were affected by viral diseases seemingly transmitted by BPH and other insect vectors, which amounted to a loss of US$120 million (Pham et al., 2007). These figures highlight the economic impact of BPH on rice production, emphasizing the need for effective pest management strategies to mitigate these losses.

Host plant resistance (HPR) is a key component of any pest management strategy because it is an effective, practical, economical, environmentally friendly, and easiest way of managing pests. Crop variety resistance to insects' damage can be based on direct and or indirect defense mechanisms, which can be constitutively present or induced upon herbivore attack (Eyidozehi et al., 2015). The plant possesses pre-adoptive genetically inherited characteristics with relation to HPR, thereby enabling a plant to avoid inhibited oviposition and damage, decelerate survival and development, and tolerate or recover from infestation of insects under economic threshold level (ETL). These mechanisms are generally governed by the physio-chemical characteristics of the plants, thereby influencing the behavior and biology of insects.

The most fanciable attribute of HPR is that it is a screening technique to ensure the resistance level of crop varieties against insect pests, so farmers do not need extra skill for application and require no additional cash investment. Although, resistance breeding programs are limited to a few crop pests only. Varietal resistance to control insect pests could provide a base for developing an integrated pest management (IPM) program. Seeds of a resistant host plant produce adverse effects on insect pest larvae during feeding and may also have a combination of morphological and biochemical features of the host plant (Aashish et al., 2021; Babu et al., 2022; Muduli et al. 2023; Meher et al., 2024). From this perspective, we need to identify the resistant sources against insect pests and incorporate these resistant QTLs/genes into the cultivating varieties.

2. Exploration of BPH-resistant germplasm

India is the native for many rice germplasm and landraces with diverse morphological and genetic variability against different stresses. Many traditional landraces are being substituted with high-yield varieties to meet the increasing food requirement. In spite of being less productive, landraces comprise various resistant traits that can be explored for rice improvement (Kumar et al., 2020). ICAR-NRRI is one of the oldest institutes in rice research and development in India and Asia as a whole. Since its inception, more than 30000 rice germplasm accessions of cultivated and wild origin were explored, characterized and conserved under various gene bank modules with storage facilities at varying durations. Some of the germplasm resources have already been utilized successfully in rice breeding, and NRRI has been released today around 188 high-

yielding, including climate-resilient and biofortified rice varieties. However, the huge genetic diversity present among available germplasm is yet to be properly exploited. Moreover, due to excessive selection pressure when creating today's modern or improved rice varieties, the genetic base has naturally been narrowed. Therefore, it has become increasingly important to transfer and pyramid the beneficial alleles from the available germplasm.

The Jeypore tract of Odisha is a well-known secondary center' of the origin of rice and possesses many rice landraces (Patra and Dhua, 2003). In 1955, NRRI scientists led by Dr. N. Parthasarathy undertook its first planned exploration and collection mission on rice germplasm in the Jeypore tract (now Koraput district of Odisha). This mission was popularly known as the Jeypore Botanical Survey and was the first of its kind ever organized in the world to collect rice germplasm. They collected a total of 1745 cultivated rice and 150 wild rice accessions. Likewise, during 1965-69, the NRRI team visited Manipur and Nagaland and collected 874 germplasms. Later on, during 1970-79, a team led by Dr. JK Roy collected about 7387 germplasm from all over India. Similarly, from 1990-2018. NRRI scientists collected 3848 germplasm from different states of India (Patra et al., 2018). During one such exploration, NRRI scientists collected 650 farmers' varieties of Odisha and brought them to the NRRI gene bank facility. After proper documentation, these Odisha farmers' germplasms were shared with the entomologist for trait verifications.

3. Characterization and evaluation of germplasm for BPH resistance

To date, four BPH biotypes have been reported worldwide, of which biotype 4 is the most destructive biotype predominant in South Asian countries, particularly in the subcontinent landscape of India. As BPH continuously evolves with the host plant, it is necessary to identify new resistant sources for sustainable management of this pest. Additionally, as the biotypes break resistance sources in the field quickly, scientists need to access new donor materials to control the spread of this pest, and hence, regular screening is required.

The rice germplasm was screened under greenhouse conditions to ascertain their level of resistance to BPH following the Standard Seed Box Screening Test (CST) method of IRRI (2002, 2013) with suitable modifications (Jena et al., 2006; 2015). Brown plant hopper

nymphs of the same stage (2nd instar) and rice seedlings of uniform age (10 days old) of all the varieties were used for the experiment**.** To obtain the desired BPH population, gravid females were released on 45 to 60-day-old potted plants of variety TN1 in test cages and were allowed to oviposit for 48 hours. Genotypes were sown in complete randomized design (CRD). Release of gravid females in rearing cages was synchronized in such a way that 2nd instar nymphs were released artificially on 10-day-old test plants @ 10-12 insects per plant and were observed daily for damage by the BPH. Observation on the percent dead seedlings was recorded for each genotype when all the seedlings of susceptible check TN1 died due to feeding of insects. The percent seedling death in each genotype was converted to a resistant or susceptible score of 1 (Highly resistant), 3 (Resistant), 5 (Moderately resistant), 7 (Susceptible) and 9 (Highly susceptible) as per the Standard Evaluation System (SES) of IRRI, Philippines (IRRI, 2013) but modified with plant mortality (Figure 3). Wherever replicated screening was carried out, the plant mortality data for all genotypes was subjected to scoring and the response of genotypes to BPH was worked out by taking the mean scoring for comparison.

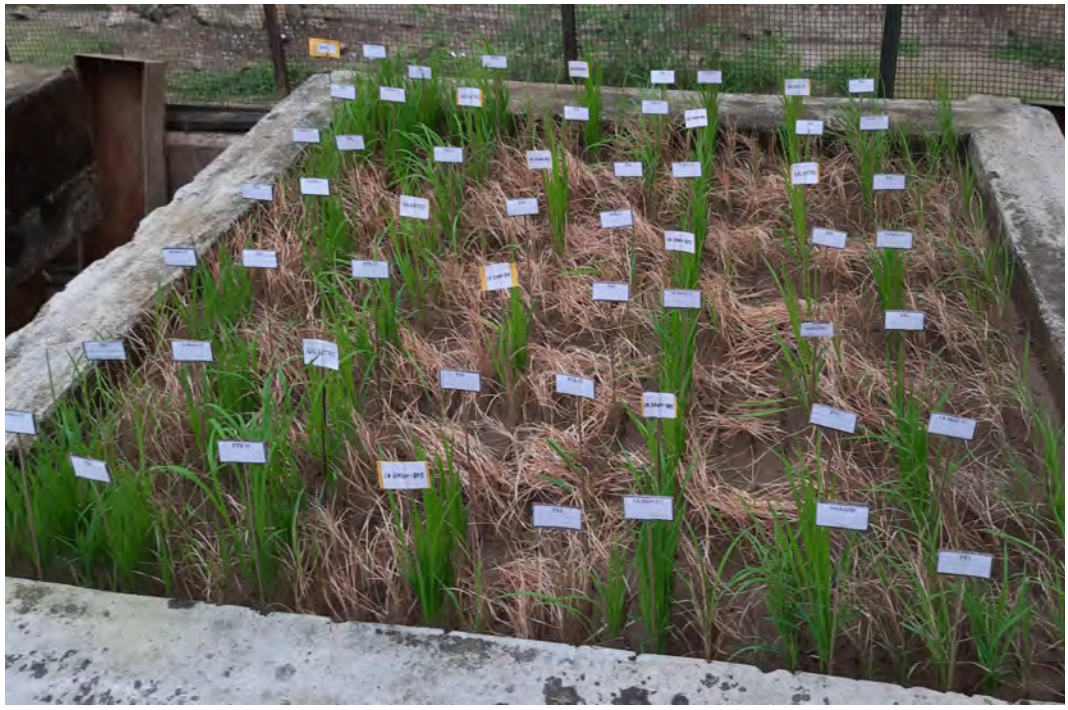

Figure 3. Screening of germplasm against brown planthopper following the SES method

At NRRI, rice collections from different states were screened for their resistance level from inception to the present. 14879 germplasm belongs to landraces and wild species; developed varieties and breeding lines have been screened against BPH (Table 2). Among those, 598 accessions were found to be highly resistant against BPH, with a resistant score of 1. Dhobanumberi and Salkathi showed consistent resistance (Score 1) for 14 years, CR Dhan 317 (CR 2711-76), CR 3006-8-2 showed high resistance (Score 1) for 11 years and RP-2068-18-3-5 showed high resistance (Score 1) for six years, whereas material from Odisha farmers variety namely Jaidubi, Jaigudi/kh-12, Kakudimanji-p, Laghu santi, Landi, Langudi, Akula, Balangir-Kahaliapalin-Assamchudi, Assamchudi, Ngrh-bhapur-Baigan Marji, Balibha Jan-j, Champa, NgrhbhapurChampesiali, GanjeiJata, Dkl/Harishankar, Kakudimanji-g, Balangir-mirdhapali Kalakrushna, Balangir-Kalajira, Kalama, Kalikati-s, Kanak champa, Katkala, Kevtia, Kuja, Lucheie, Parijat, Yada showed high resistant (score) for consecutive three years against rice brown planthopper. Besides, IC322922, IC75881, IC426149, IC256515, IC273558, IC426148, IC426126, IC256545, IC346890, IC346237, IC256547, IC752742, IC574971, IC75883, IC283249, IC426092, IC256849, IC346892, IC752742, and IC256545 showed consistently moderately resistant for three years. Whereas popular varieties (Naveen, Swarna, Pooja) showed susceptible reactions (Score 9) for four consecutive years (Table 3).

Table 2. Germplasm screened against BPH at NRRI (Source: NRRI Annual Report: 1950-2022)

Sl No	Insect Pest	Scientific Name	Total Number of genotypes	Number of resistant genotypes	Notable BPH-resistant accessions
1	Brown Planthopper (BPH)	*Nilaparvata lugens*	14879	598	Salkathi, Dhobanumberi, Assamchudi, Baiganmanji, Champa, Champeisiali, Balibhanjana-T, Ganjeijota-P, Jalakanthi, Banaspati, Panidubi, Harishankar, etc.

Table 3. List of important resistant germplasm against Brown Planthopper

Sl No	Name of Germplasm	Year of testing (multiple years)	Frequency of testing (Number)	Values (score) in multiple testing	Remarks (Tolerant/ MR/R/ etc)	Reference
1	Dhobanumberi	2009-2022	14	1	HR	Jena et al., (2022)
2	Salkathi	2009-2022	14	1	HR	Jena et al., (2022)
3	CR Dhan 317	2012-2022	11	1	HR	Jena et al., (2022)
4	CR 3006-8-2	2012-2022	11	1	HR	Jena et al., (2022)
5	RP-2068-18-3-5	2017-2022	6	1	R	Jena et al., (2022)
6	Jaidubi	2018-2020	3	1	HR	Anant et al., (2022)
7	Jaigudi/kh-12	2018-2020	3	1	HR	Anant et al., (2022)
8	Kakudimanji-p	2018-2020	3	1	HR	Anant et al., (2022)
9	Laghu santi	2018-2020	3	1	HR	Anant et al., (2022)
10	Landi	2018-2020	3	1	HR	Anant et al., (2022)
11	Langudi	2018-2020	3	1	HR	Anant et al., (2022)
12	Akula	2018-2020	3	1	HR	Anant et al., (2022)
13	Balangir-Kahaliapalin-Assamchudi	2018-2020	3	1	HR	Anant et al., (2022)
14	Ngrh-bhapur-Baigan Marji	2018-2020	3	1	HR	Anant et al., (2022)
15	Balibha Jan-j	2018-2020	3	1	HR	Anant et al., (2022)

16	Champa	2018-2020	3	1	HR	Anant et al., (2022)
17	Ngrhbhapur Champesiali	2018-2020	3	1	HR	Anant et al., (2022)
18	GanjeiJata	2018-2020	3	1	HR	Anant et al., (2022)
19	Dkl/Harishankar	2018-2020	3	1	HR	Anant et al., (2022)
20	Kakudimanji-g	2018-2020	3	1	HR	Anant et al., (2022)
21	Balangir-mirdhapali Kalakrushna	2018-2020	3	1	HR	Anant et al., (2022)
22	Balangir-Kalajira	2018-2020	3	1	HR	Anant et al., (2022)
23	Kalama	2018-2020	3	1	HR	Anant et al., (2022)
24	Kalikati-s	2018-2020	3	1	HR	Anant et al., (2022)
25	Kanak champa	2018-2020	3	1	HR	Anant et al., (2022)
26	Katkala	2018-2020	3	1	HR	Anant et al., (2022)
27	Kevtia	2018-2020	3	1	HR	Anant et al., (2022)
28	Kuja	2018-2020	3	1	HR	Anant et al., (2022)
29	Lucheie	2018-2020	3	1	HR	Anant et al., (2022)
30	Parijat	2018-2020	3	1	HR	Anant et al., (2022)
31	Yada	2018-2020	3	1	HR	Anant et al., (2022)
32	IC322922	2020-2021-2022	3	1	HR	Babu et al., (2023)
33	IC75881	2020-2021-2022	3	1	HR	Babu et al., (2023)

34	IC426149	2020-2021-2022	3	1	HR	Babu et al., (2023)
35	IC256515	2020-2021-2022	3	1	HR	Babu et al., (2023)
36	IC273558	2020-2021-2022	3	1	HR	Babu et al., (2023)
37	IC426148	2020-2021-2022	3	1	HR	Babu et al., (2023)
38	IC426126	2020-2021-2022	3	1	HR	Babu et al., (2023)
39	IC256545	2020-2021-2022	3	1	HR	Babu et al., (2023)
40	IC346890	2020-2021-2022	3	1	HR	Babu et al., (2023)
41	IC346237	2020-2021	2	1	R	Babu et al., (2023)
42	IC256547	2020-2021	2	1	R	Babu et al., (2023)
43	IC752742	2020-2021	2	1	R	Babu et al., (2023)
44	IC574971	2020-2021	2	1	R	Babu et al., (2023)
45	IC75883	2020-2021	2	1	R	Babu et al., (2023)
46	IC283249	2020-2021	2	1	R	Babu et al., (2023)
47	IC426092	2020-2021	2	1	R	Babu et al., (2023)
48	IC256849	2020-2021	2	1	R	Babu et al., (2023)
49	IC346892	2020-2021	2	1	R	Babu et al., (2023)
50	IC752742	2020-2021	2	1	R	Babu et al., (2023)
51	IC256545	2020-2021	2	1	R	Babu et al., (2023)

52	Naveen	2019-2022	4	9	HS	Jena et al., (2022)
53	Swarna	2019-2022	4	9	HS	Jena et al., (2022)
54	Pooja	2019-2022	4	9	HS	Jena et al., (2022)

3.2. Screening of germplasm collected from farmers of Odisha against BPH

NRRI scientists screened the Odisha farmer's varieties from 2000 to 2002. Out of 600 varieties, 11 showed high resistance to BPH (Figure 4). They were-Nagnasitasali (AC42688), Jhup jhupa (AC34997), Sahiba (AC35003), Panidubi (AC35070), Dhoiya bankoi (AC35155), Salkathi (AC35181), Jhulpuagi (AC35183), Dhobanumberi (AC35184), Jalakanthi (AC35228), Chaka akhi (AC35677) and Palasphula (AC35703). Other 13 like Bharat Sandha (AC42687), Sutasali (AC42715), Banka (AC34999), Kalamdani (AC35021), Lankeswari (AC35032), Chudi (AC35077), Ratanchudu (AC35082), Sapuri (AC35088), Manipuri (AC35091), Gauri kajli (AC35097), Matia champa (AC35195), FARM 242 (AC35199) and Bahalmali (AC35222) showed resistant reaction of score 3. The resistant varieties of score 1 were subjected to replicated screening. Only Accession Numbers AC34997, AC 35003, AC 35070, AC35155, AC35181,

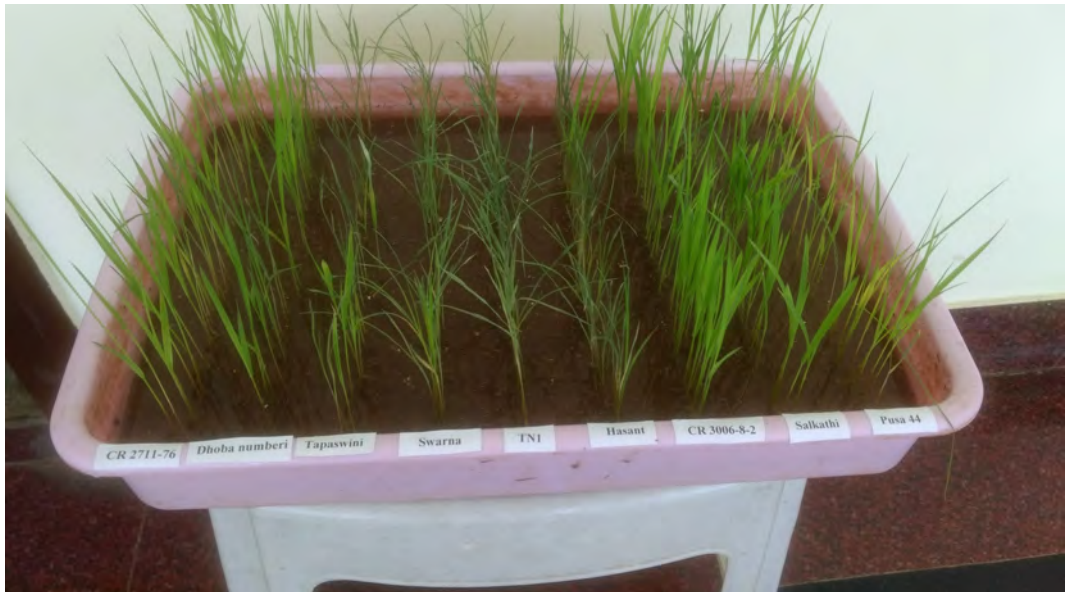

Figure 4. Screening of Odisha Farmers' varieties against Brown Planthopper

AC35184 and AC35228 kept the same status, whereas the rest showed a reaction of score 3 (Jena et al., 2006). From this screening, 2 accessions, namely, Salkathi and Dhobanumberi, were further selected for breeding programs.

3.3. Screening of Assam rice accessions against Brown Planthopper

Assam rice accessions 1665 were screened against brown planthoppers in 1979, and 38 resistant germplasm with an SES score of 1 were found. The details of the resistant germplasm as follows: ARC 5779, 10468, 10508, 10573, 10583, 10520,10836, 11689, 11971, 12035, 12197, 12411, 12538, 12659, 12760, 13501, 13764, 14073, 14515, 14563, 14566, 14588, 14620, 14636-A, 14678, 14765, 15358, 15561, 18224, 18265, 18502, 14774, 11998, 12655, 5832, 11712, 18130, and 12416. Assam rice accessions 200 were screened against brown planthopper during 2016-17. Of these, only four Assam rice accessions (ARC 333, 356, 11324 and 11309) had an SES score of 1.

3.4. Screening of Manipur rice accessions against Brown Planthopper

Manipur rice accessions 102 were screened against brown planthopper. Of which, only six Manipur rice accessions (AC-9019, AC-9053(A), AC-9060, AC-9063, AC-9074(A), and AC-9080) with plant damage score of 3 and damage percentage of 27.33%, 17.44%, 23.31%, 17.38%, 29.71% and 26.79%, respectively; were classified as Resistant (R). All remaining accessions along with TN1 (Susceptible check) exhibited a plant damage score of 9 with a damage percentage of 80-100% categorized as highly susceptible; on the other hand, resistance checks, Salkathi, and Ptb33 recorded a score of 1 and damage percentage of 8% and 4%, respectively, categorized as highly resistant to BPH.

4. Multi-location trial for BPH resistance

The identified resistant germplasm/wild relatives were shared with national (AICRIP; PAU, IARI) and international partners for the advancement of brown planthopper resistance. Evaluation of genotypes against brown planthopper in PHS trail during 2003 and 2004 revealed that both Salkathi and Dhobanumberi were found promising against BPH in all India level showing resistant reaction against BPH population of Hyderabad, Coimbatore, Mandya, Maruteru, Cuttack, Ludhiana and Raipur (Table 4). The breeding lines developed by the crossing of Dhobanumberi and Tapaswini were also tested in the

AICRIP multi-location trial. The lines (CR2711-76, CR2711-114, CR2711-139, CR2711-149, and CR2712-2) developed from the above cross showed consistent resistant reactions against BPH during 2009 and 2010 across the different locations (Table 4). Further, the resistant landraces Salkathi (INRG17069) and Dhobanumberi (19005) were registered at ICAR-NBPGR germplasm for brown planthopper resistance trait.

Table 4. Reaction of genotypes against BPH in planthopper screening trial of AICRIP

Year	Entry No	Designation	Green House's/Field reaction against BPH						
			Hyderabad	Coimbatore	Mandya	Maruteru	Cuttack	Ludhiana	Raipur
2003	15	Dhobanumberi	3.0	3.0	0.0	3.0	3.0	-	-
	28	Salkathi	2.2	3.0	0.0	3.0	3.0	-	-
	20	PTB33	1.4	5.0	0.0	1.0	3.0	-	-
2004	8	Dhobanumberi	8.2	3.0	-	-	-	3.0	-
	35	Salkathi	2.9	3.0	0.0	1.0	1.0	-	-
	20	PTB33	1.1	3.0	3.0	-	5.0	5.0	-
2009	9	CR2711-76	1.7	3.0	1.0	444	-	-	2.1
	11	CR2711-114	1.2	3.0	1.0	540	-		1.0
	12	CR2711-139	1.4	3.0	1.0	494	-		2.3
	13	CR2711-149	1.1	3.0	1.0	339	-		1.0
	14	CR2712-2	1.7	5.0	1.0	294	-		1.9
	20	PTB33	2.7	7.0	1.0	516	-		0.9
2010	23	CR2711-76	3.0	3.0	3.0	-	3.0	3.0	3.0
	26	CR2711-149	3.0	3.0	3.0	-	3.0	3.0	3.0
	24	CR2711-114	3.0	3.0	3.0	-	3.0	3.0	3.0
	25	CR2711-139	3.0	3.0	3.0	-	3.0	3.0	3.0
	27	CR2712-2	3.0	3.0	3.0	-	3.0	3.0	3.0
	20	PTB33	3.0	3.0	3.0	-	3.0	3.0	3.0

Multiple resistance screening trials were conducted with 9 lines of NRRI during 2011 and 2012 at 26 locations with 50 tests across India. Among them, CR 2711-76 and CR3006-8-2 displayed resistant reactions at 13 and 8 tests against multiple pests (Table 5). CR 2711-76 and CR3005-230-5 showed promising results against planthoppers in 6 of the 12 locations. Similar results were obtained during the test year 2012.

Table 5 Performance of most promising entries against pest in MRST of AICRIP

Year	Entry No	Designation	Green House's/Field reaction in different centers against rice pest							
			BPH	WBPH	GLH	PH	GM	SB	WM	GB
2011	9	CR3005-230-5	3	1	1	1	0	5	2	0
	1	CR2711-76	3	1	1	1	1	0	0	1
	7	CR3005-77-2	2	1	1	1	1	3	0	0
	11	CR3006-8-2	3	1	1	0	1	2	0	0
	20	Suraksha	1	0	2	0	2	1	0	1
2012	1	CR2711-76	-	-	-	7	0	5	0	1

BPH – Brown planthopper; WBPH – White-backed brown planthopper; GLH – Green leafhopper; PH – planthoppers; GM- Gall Midge; SB – Stem borer; WM – Whorl maggot; GB – Gundhi bug

5. Identification of QTLs/Genes in the BPH-resistant germplasm

Four BPH biotypes have been found worldwide, of which, biotypes 1 and 2 are widely distributed in Southeast and East Asia, and biotype 3 was developed in the laboratory by rearing the insects on the resistant variety ASD7, which has the *bph2* gene for resistance (Panda and Heinrichs, 1983). The most destructive biotype-4 occurs in the Indian subcontinent and is also called the South Asian biotype (Aashish et al., 2021; Babu et al., 2022; Meher et al., 2024)). Cultivars with *Bph1* gene confer resistance to biotypes 1 and 3 but are susceptible to biotype 2. The *bph2* gene confers resistance to biotype 1 and 2 but not to biotype 3. The *Bph3* and *bph4*, *bph8*, and *Bph9* genes confer resistance to all four biotypes. Genes such as *bph5*, *bph6*, and *bph7* confer resistance to biotype 4 only (Brar et al., 2009). The continuous growth of resistant varieties may lead to certain

physiological and behavioural changes in insect pests so that they can feed and develop on the resistant variety (Dhaliwal and Arora, 2020). To date, very few genes are available that confer resistance against all four biotypes of BPH. Entomologists and plant breeders develop varieties that contain a gene which combats insect pests and maintains the genetic diversity of crops at the same time. Hence, to overcome the BPH-associated problem, major efforts have been made to discover new resistance sources from wild and cultivated rice germplasm (Yan et al., 2023; Li et al., 2024). As far as BPH resistance, now, 46 genes have been explored in both cultivated varieties and wild species (Table 6) of rice (Mishra et al. 2022; Yan et al. 2023; Li et al. 2024). In addition to major genes, many quantitative trait loci (QTLs) associated with BPH resistance have been discovered in cultivated and wild rices, and mapped to different chromosomes 1, 2, 3, 4, 6, 7, 8, 10, and 12 (Mishra et al. 2022; Yan et al. 2023). The few major genes (*Bph1, bph2, Bph3, Bph9, Bph12, Bph14, Bph15, Bph17, Bph18, Bph25, Bph26, Bph27,* and *Bph32), and QTLs qBph 12, qBph3, and qBph4* have been introgressed into elite rice susceptible cultivars through a marker-assisted breeding approach (Yan et al. 2023). A total of 17 genes associated with BPH resistance (*Bph1, Bph2, Bph3, Bph6, Bph7, Bph9, Bph10, Bph14, Bph15, Bph18, Bph21, Bph26, bph29*, *Bph30*, *Bph32, Bph37, and Bph40)* have been cloned to understand molecular mechanisms of BPH resistances. Eight of these genes (*Bph2, Bph7, Bph9, Bph10, Bph18, Bph21,* and *Bph26)* are multiple alleles of the same locus. These genes primarily encode five types of proteins: lectin receptor kinase (LRK), coiled-coil-nucleotide binding-leucine rich repeat (CC-NB-LRR), B3-DNA binding domain, leucine-rich repeat domain (LRD), and short consensus repeat (SCR) (Mishra et al. 2022; Yan et al. 2023).

Table 6. BPH resistance genes, source material and chromosome location

Sl No	Resistance Gene	Source	Chromosome No
1	*BPH1*	Mudgo, IR64, TKM6	12
2	*BPH2*	Ptb33, ASD 7, IR36	12
3	*bph2*	IR1154-243	12
4	*BPH3*	Ptb33, Rathu Heenati, *O. officinalis* (Acc. No. 100896)	6
5	*qBph3*	Rathu Heenati	3
6	*qBph3*	*O. officinalis*	3

7	*BPH4*	Babawee	6
8	*qBph4.1*	*O. officinalis*	4
9	*qBph4.2*	*O. australiensis*	4
10	*BPH5*	ARC 10550	-
11	*Bph6*	Swanalata, *O. officinalis* (Acc. No. 100896)	4
12	*Bph7*	T12	12
13	*Bph8*	ChinaSaba, Col. 5, Col. 11	-
14	*Bph9*	Pokkali, Balamawee, Kaharamana	12
15	*BPH10*	*O. australiensis, O. officinalis*	12
16	*qBph10*	Rathu Heenati	10
17	*Bph11*	IR154-243, *O. officinalis*	3
18	*qBph11*	DV85	11
19	*Bph12*	*O. latifolia*	4
20	*Bph13(t)*	*O. officinalis* (acc. 100896)	3
21	*Bph14*	B5 (*O. officinalis*)	3
22	*Bph15*	B5 (*O. officinalis*)	4
23	*Bph16*	-	4
24	*Bph17*	Rathu Heenati	4
25	*Bph18*	*O. australiensis* (Acc, No. 100882)	12
26	*bph19*	AS20-1	3
27	*Bph20*	*O. minuta* (acc. 101141)	4
28	*Bph21*	*O. minuta* (acc. 101141)	12
29	*Bph22(t)*	*O. rufipogon*	4
30	*Bph23(t)*	*O. rufipogon*	8
31	*Bph24(t)*	*O. rufipogon*	-
32	*BPH25*	ADR52	6
33	*Bph26*	IR1154-243	12

34	*Bph27*	GX2183 (*O. rufipogon*)	4
35	*Bph27(t)*	Balamawee	4
36	*Bph28(t)*	DV85	11
37	*BPH29*	RBPH54 (*O. rufipogon*)	6
38	*BPH30*	AC-1613	4
39	*BPH31*	CR2711- CR Dhan 317, Dhobanumberi	3
40	*BPH32*	Ptb33	6
41	*BPH33*	KOLAYAL, POLIYAL	4
42	*Bph33(t)*	RP2068	1
43	*Bph34*	IRGC 104646 (*O. nivara*)	4
44	*Bph35*	RBPH660	4
45	*BPH36*	*O. rufipogon* Griff	4
46	*Bph37*	IR64	1
47	*BPH38(t)*	Khazar	1
48	*bph39(t)*	*O. nivara*	-
49	*Bph40(t)*	*O. nivara*	-
50	*BPH41*	SWD10	4
51	*BPH42*	SWD10	4
52	*Bph43*	IRGC 8678	11
53	*Bph44*	Balamawee	4
54	*Bph45*	*Oryza nivara* (IRGC 102165), TNG71	4
55	*Bph46*	*Oryza nivara* accession IRGC 93198	4

The identification of QTLs with different mechanisms of host plant resistance and their introduction into elite cultivars is essential for slowing down the breaking of resistance. We conducted experiments to identify QTLs/genes associated with resistance to BPH in the resistant *indica* landrace Salkathi. A recombinant inbred line (RIL) mapping population was developed from the cross between TN1 (susceptible) and Salkathi (resistant) following

the single seed-descent method. Phenotyping of 300 RILs against the BPH population at Cuttack, Odisha, showed continuous skewed variation with four peaks at 2.1–3.0, 4.1–5.0, 6.1–7.0, and 8.1–9.0 SES scores, suggesting the involvement of quantitative loci for resistance to BPH in Salkathi (**Figure 5**). A total of 178 RILs were found to be susceptible, whereas 122 RILs were resistant. The Chi-square test showed that the segregation of susceptible plants to resistant plants in RILs fitted into a 9:7 ratio (Chi-square value: 1.56, P<0.1), indicating the involvement of two QTLs/genes in controlling resistance to BPH. 698 microsatellite markers were employed to survey polymorphism between Salkathi and TN1. 92 markers were found to be polymorphic, which were used to genotype 300 RILs. QTL analysis using QTL IcMapping software identified two BPH resistance QTLs, *qBph4.3* and *qBph4.4,* with LOD scores of 34.2 and 4.61, respectively, on the short arm of chromosome 4 between RM551-RM518 and RM335-RM5633, respectively, in the resistant landrace Salkathi. These QTLs explained phenotypic variances of 37.02% and 7.1%, respectively (**Figure 6; Table 7**). 69.01% of the phenotypic variance was contributed to BPH resistance by an epistatic interaction between these two QTLs, with a LOD score of 6.93 (Mohanty et al., 2017). Further, this RIL population was genotyped with a high-density SNP marker chip (40K Affymetrix SNP Array chip). QTL analysis led to the identification of these QTLs, *qBph4.3* and *qBph4.4,* to 0.62 to 1.39 Mb and 18.63 to 23.85 Mb regions on chromosome 4 (**Figure 7**). Salkathi has been used to successfully transfer BPH resistance into two elite rice cultivars, Pusa 44 and Samba Mahsuri, following conventional approaches. The presence of these two QTLs, *qBph4.3* and *qBph4.4,* was validated in two resistant breeding lines, CR3008-2 (Pusa 44/Salkathi) and CR3005-230-5 (Samba Mahsuri).

Table 7. QTLs identified for resistance to BPH in the RIL population derived from the cross between TN1 and Salkathi

QTL	Marker interval[a]	Chrom#	QTL Position (cM)	Distance from closest marker (cM)	LOD score	PVE%	Additive effect[b]
qBph4.3	RM551-RM335	4(LG8)	18.0	0.56	34.2	37.02	-1.75
qBph4.4	RM335-RM5633	4(LG8)	31.0	8.23	4.61	7.10	-0.77

[a] Bold letter shows the closest marker to QTL
[b] Negative values of additive effect indicate that the resistance allele was inherited from Salkathi

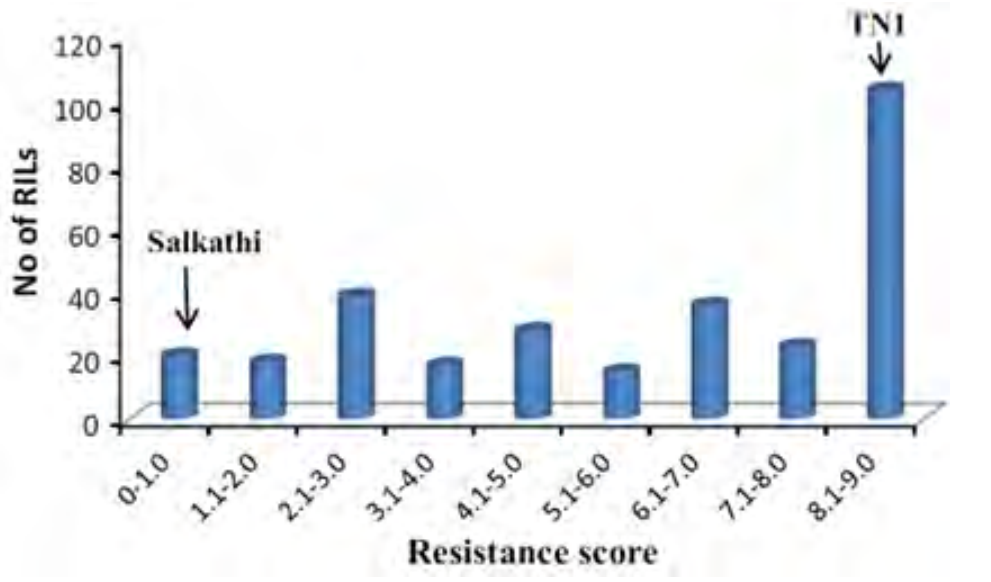

Figure 5. Frequency distribution of BPH resistance scores among RILs developed from the cross between TN1 and Salkathi. The mean resistance scores of Salkathi and TN1 were indicated by arrows. Source: Mohanty et al. (2017)

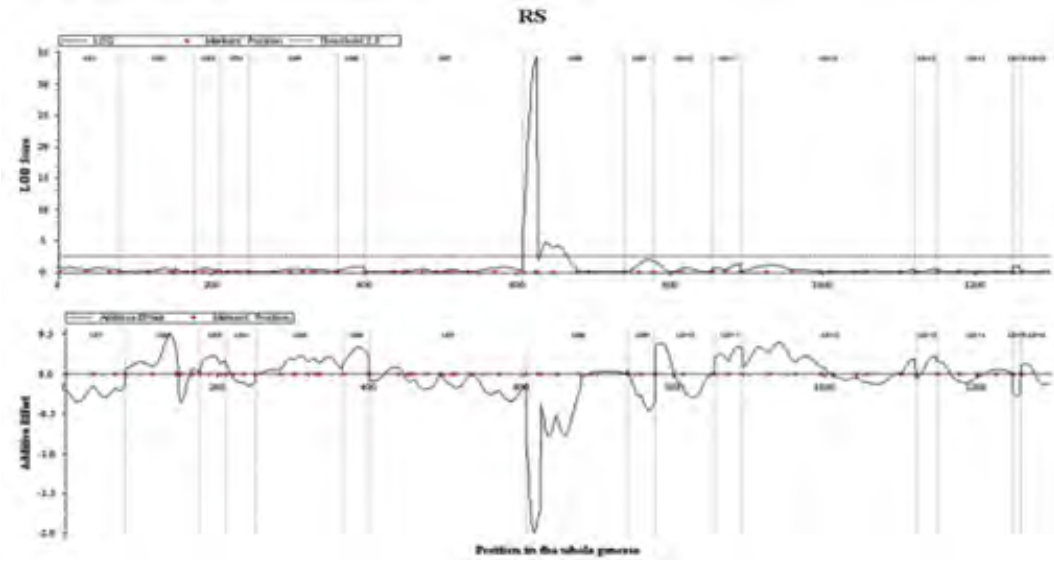

Figure 6. One-dimensional scanning of whole genome for identification of QTLs associated with BPH resistance in Salkathi using QTL IcMapping software. Upper half shows position of QTLs on linkage group8 (chromosome 4) with LOD score while lower half shows additive effects of QTLs. Two peaks corresponding to two QTLs (*qBPH4.3* and *qBph4.4*) were identified on LG8 (chromosome 4).

Source: Mohanty et al. (2017)

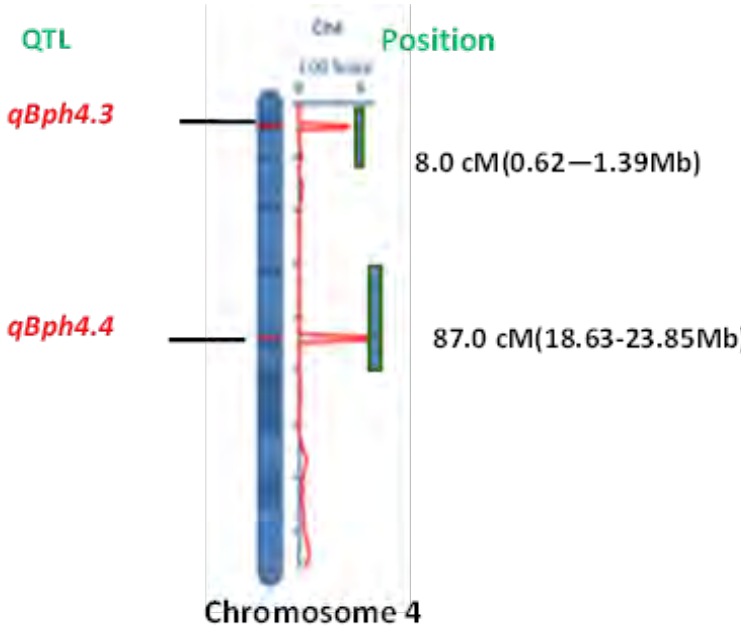

Figure 7. Positioning of *qBPH4.3* and *qBph4.4* associated with BPH resistance using 40K SNP genotyping of same RIL population.

BILs were developed from the cross between the elite susceptible variety Naveen and the resistant breeding line CR3006-8-2 (Pusa44/Salkathi) using molecular markers linked to QTLs, *qBph4.3* and *qBph4* described in the subsequent section. Promising resistant BILs were identified. One of the resistant BIL was crossed with Naveen, and 420 intercross lines (IC1F6) lines were developed. These IC1F6 were phenotyped against BPH and were genotyped with 16 polymorphic markers in QTLs regions on chromosome 4 (between 0-26Mb). QTL analysis confirmed two regions (0.62-1.39 Mb for *qBph4.3* and 18.63-23.85 Mb for *qBph4.4*) associated BPH resistance. *In silico* analysis identified 15 and 10 putative candidate genes *qBph4.3*, and *qBph4.4* regions, respectively. Expression analysis of these 25 putative candidate genes in resistant parents (Salkathi and CR3006-8-2 (Pusa44/ Salkathi) and susceptible parents (TN1 and Naveen) identified 10 genes associated with resistance QTLs in Salkathi. Further, expression analysis of these 10 putative candidate genes in resistant (Salkathi and CR3006-8-2 (Pusa44/Salkathi), susceptible (TN1 and Naveen) parents and 12 BILs (four resistant, two moderately resistant, two susceptible, and four highly susceptible) developed from Naveen and CR3006-8-2 identified seven

genes, NBS-LRR, ZOS4-01-C2H2 zinc finger protein, Leucine-rich repeat family protein, disease resistance protein RPM1, Leucine-rich repeat family protein, Serine/threonine-protein kinase receptor, and serine-threonine protein kinase are likely to be potential candidate genes for BPH resistance. Further, work is continuing to validate these potential candidate genes in resistant NILs containing single or both of these QTLs.

The resistant breeding line, CR2711-76, was developed from the cross between the elite cultivar Tapaswini and BPH-resistant landrace, Dhobanumberi, at the National Rice Research Institute (NRRI), Cuttack, Odisha, India. It showed stable and broad-spectrum resistance to several BPH populations of the Philippines and biotype 4 of India (Annual Report, DRR, 2012; Prahalada et al., 2017). In order to identify QTLs/genes present in resistant the breeding line, CR2711-76, mapping populations of $F_{2:3}$, BC_1F_1, and BC_2F_2 were developed from the cross between the popular susceptible variety, Jaya, and CR2711-76, and

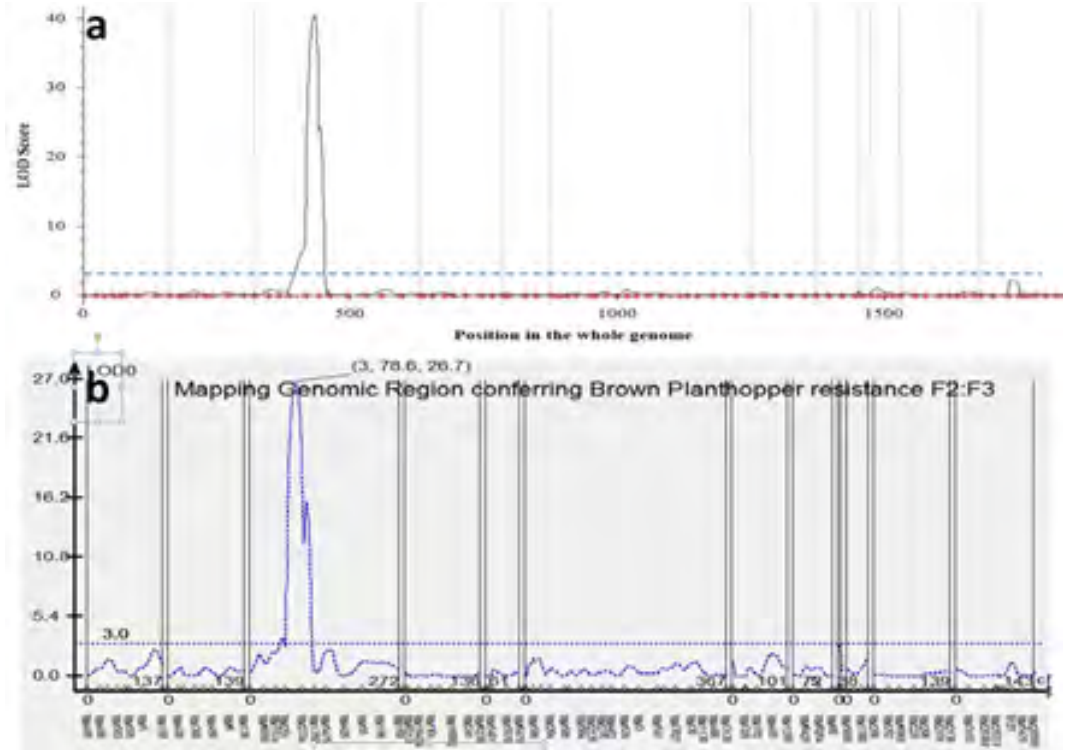

Figure 8. One-dimensional scanning of whole genome for identification of genomic region associated with BPH resistance in CR2711–76 using QTL IcMapping software (a) and WinQTL Cartographer software. Source: Adopted from Prahalada et al. (2017)

screened against BPH populations at IRRI, Philippines. The segregation pattern indicated that a single dominant gene controlled BPH resistance in CR2711-76. 151 F_2 lines were genotyped with 107 polymorphic markers. Linkage and QTL analysis using QTL IciMapping software identified a single major locus on the long arm of chromosome 3 between the SSR markers RM251 and RM2334, spanning a region of 24.30 cM with an LOD score greater than 38 (**Figure 8a**). A similar result was obtained by analysis with WinQTL Cartographer software (**Figure 8b**). The putatively identified new resistance gene was named *BPH31* (Prahalada et al., 2017). In order to fine-tune the map, 27 InDel markers in the *BPH31* region were designed and tested in the parents. Four markers showed polymorphism, and these InDel markers were used to screen the same 152 F_2 population, and linkage analysis was carried out. *BPH31* was located between the markers PA26 and RM2334 with a LOD score of 47.64 and physical distance of 475 kb, explaining 79.8% of phenotypic variance. *In silico* analysis identified 42 putative candidate genes. The functional analysis of these 42

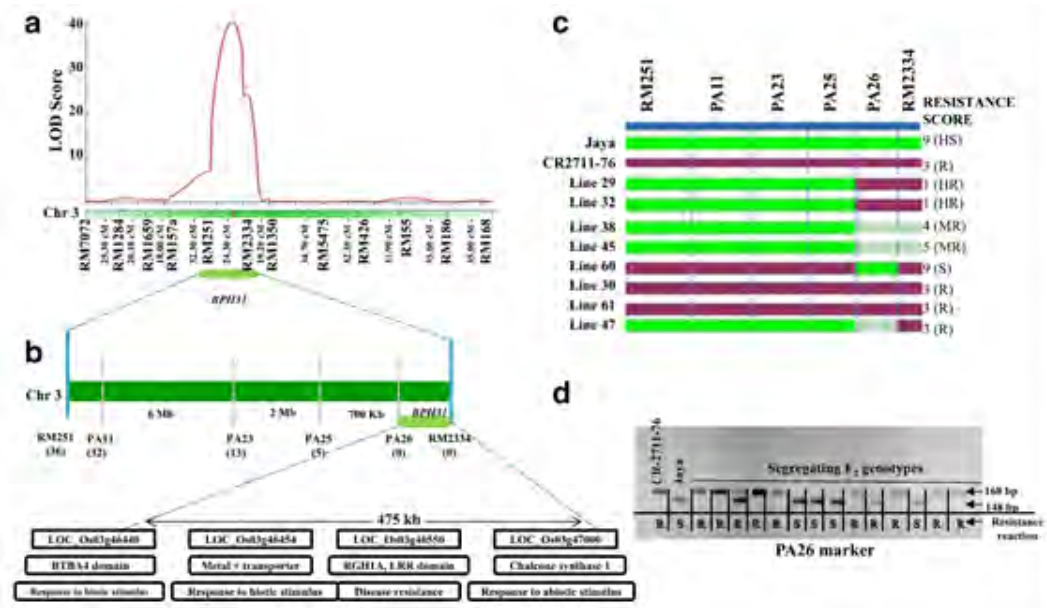

Figure 9. Primary and fine mapping of *BPH31* gene locus. A) The primary map of *BPH31* using 151 F2:3 lines. B) Physical and fine map of *BPH31* locus; gray vertical bars indicate newly designed polymorphic InDel markers for fine mapping. C) Molecular marker genotypes and phenotypes of recombinants. The green, light red, and gray bars denote the marker genotypes of Jaya homozygotes, CR2711–76 homozygotes, and their heterozygotes, respectively. d) Segregation pattern of the PA26 InDel marker with BPH resistance reaction. R and S indicate resistance and susceptible reaction of BPH respectively. Source: Adopted from Prahalada et al. (2017)

putative candidate genes revealed that three genes (*LOC_Os03g46440*, *LOC_Os03g46454*, and *LOC_Os03g46550*) might be associated with BPH resistance in the resistant breeding line CR2711-76 (**Figure 9**). The efficacy of PA25, PA26, and RM2334 markers was tested in BC_2F_2 population derived from the cross between Jaya and CR2711-76. Among these markers, PA26 and RM2334 showed the highest co-segregation. Hence, these markers were considered tightly linked markers and used for introgressing *BPH31* in Jaya background.

6. Use of the QTLs/Genes for the development of BPH-resistant varieties

Although there have been numerous studies related to morphological, biochemical and physiological mechanisms behind rice resistance to BPH, specifically developing resistant variety containing resistance QTLs/genes might be an efficient strategy to control BPH infestation (Stout, 2014; Du et al., 2020; Anant et al., 2021). Modern-day high-yielding varieties lack resistance against biotic stress, particularly against BPH. Therefore, it is necessary to discover and describe novel BPH resistance QTLs/genes for secure rice production because the identification of the resistance sources alone does not solve the problem. Hence, it is essential to locate the gene along with tightly linked molecular markers for the respective resistant gene. Further, it is important to note that future host plant resistance programs should focus on identifying the BPH-resistant genes that are effective against local BPH populations. Moreover, present rice market demands for high-yielding varieties with quality rice pose a challenge for the scientists to transmit biotic stress resistance genes to farmers' preferred elite cultivars for more economical benefits. For this reason, researchers were turned towards traditional landraces or rice varieties in search of various resistance traits due to their superiority in several traits compared to cultivated rice varieties.

The landraces collected from different places and conserved in the NRRI gene bank were screened against brown plant hopper (BPH) under artificial inoculation in net house condition at NRRI and the genotypes showing resistance reaction were screened repeatedly to know the consistency of their performance. Two landraces, Salkathi and Dhobanumberi, were found to be highly resistant against BPH for 3 consecutive years (2000-2002) and were further evaluated at multiple locations in the Planthopper Screening (PHS) trial of AICRIP in 2003 and 2004. Both genotypes were found to be promising over multiple years of testing in AICRIP (DRR Annual Progress Report, vol.2 (2003 and 2004).

6.1 Development of BPH-resistant variety through conventional breeding

These landraces were extensively used in the breeding program at NRRI, Cuttack. The breeding lines developed through pedigree breeding (Figure 10) were screened extensively against BPH at the Institute and were nominated for PHS trial of AICRIP. Four cultures CR 2711-114, CR 2711-76, CR 2711-139, and CR 2711-149 derived from the cross Tapaswini / Dhobanumbari were found to be the most promising entries in the Planthopper Screening (PHS) trial of AICRIP in 2009 and 2010 (DRR Annual Progress Report, vol.2 (2009, 2010). Further, CR 2711-76 was also found to be resistant against BPH in the Multiple resistant screening trials (MRST) of AICRIP in 2011 and 2012.

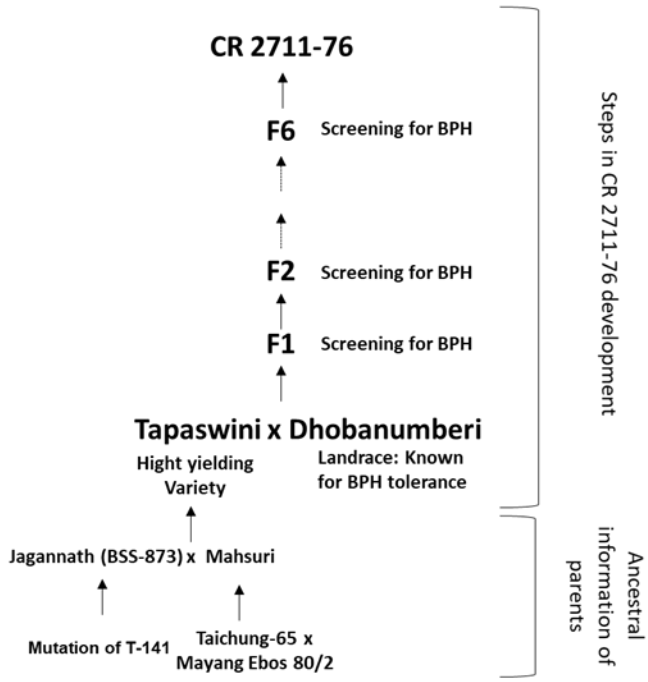

Figure 10. Breeding scheme for development of CR Dhan 317 (CR 2711-76)

Cultures that arose from the crosses using landrace Salkathi as a donor were screened at NRRI and identified three resistant cultures viz, CR 3005-230-5 (Samba Mahsuri / Salkathi), CR 3005-77-2 (Samba Mahsuri / Salkathi), and CR 3006-8-2 (Pusa 44 / Salkathi). Identified cultures were screened under Multiple resistant screening trials (MRST) of AICRIP in 2011 and 2012 (DRR Annual Progress Report, vol.2 (2011, 2012) and reported as resistant against BPH.

The *BPH31* gene was identified from the resistant genotype CR 2711-76 in collaboration with the International Rice Research Institute (IRRI) (Prahalada et al., 2017). This breeding line was also extensively tested in AICRIP yield trials and farmers' field trials. The CR 2711-76 (IET 24409) showed an average yield of 5.014 t/ha in the Eastern zone (Zone III) of India, which is 31.91% higher yield than the local check, 16.46% higher grain yield than the zonal check (Pooja), at par with national check (Swarna) (AICRIP, IVT-L-Kharif, 2014). Under the AICRIP trial of Odisha state, it registered a grain yield of 4.58 t/ha, which is much higher than the average productivity of rice in Odisha. The yield of IET 24409 (CR 2711-76) is at per with national check (Swarna) and Zonal check (Pooja), however, it showed a strong resistance reaction against BPH. Further, the trial was conducted on farmers' fields of Odisha, particularly in the endemic area of BPH. The grain yield was ranged from 3.85 to 7.28 t/ha, with an average of 5.45 t/ha under 66 farmers field trials, along with resistance/tolerance reaction to BPH. This variety was released and notified as CR Dhan 317 for Odisha in 2021 (Figure 11).

6.3. BPH-resistant varieties developed through marker-assisted backcross breeding (MABC)

The BPH-resistant rice landrace 'Salkathi' was collected from Odisha's BPH hotspot Chiplima in Sambalpur district. This line was found to be highly resistant against BPH, and two QTLs *qBph 4.3* and *qBph4.4* on chromosome 4 conferring resistance were identified at ICAR-National Rice Research Institute, Cuttack (Mohanty et al., 2017). One resistant pre-breeding line, CR 3006-8-2, was developed by hybridizing the landrace 'Salkathi' with another susceptible high-yielding cultivar, Pusa 44. CR 3006-8-2 also showed resistance all over India in AICRIP trials and was found to carry both the QTLs mapped from Salkathi. The resistant pre-breeding line CR 3006-8-2 was subsequently used in the marker-assisted backcross breeding (MABC) program for transferring the two QTLs into elite backgrounds (Figure 11). Initially, two popular varieties (Naveen and Pooja) were selected to introgress QTLs from Salkathi. Subsequently, two other popular varieties, Swarna and CR Dhan 312, were chosen, and the work is in progress.

6.3.1. Pyramiding of QTLs for BPH resistance

Three STMS markers linked to BPH resistance QTLs *qBph4.3* and *qBph4.4* were used for foreground selection of the QTLs. Additional polymorphic markers (SSRs and Indels) were

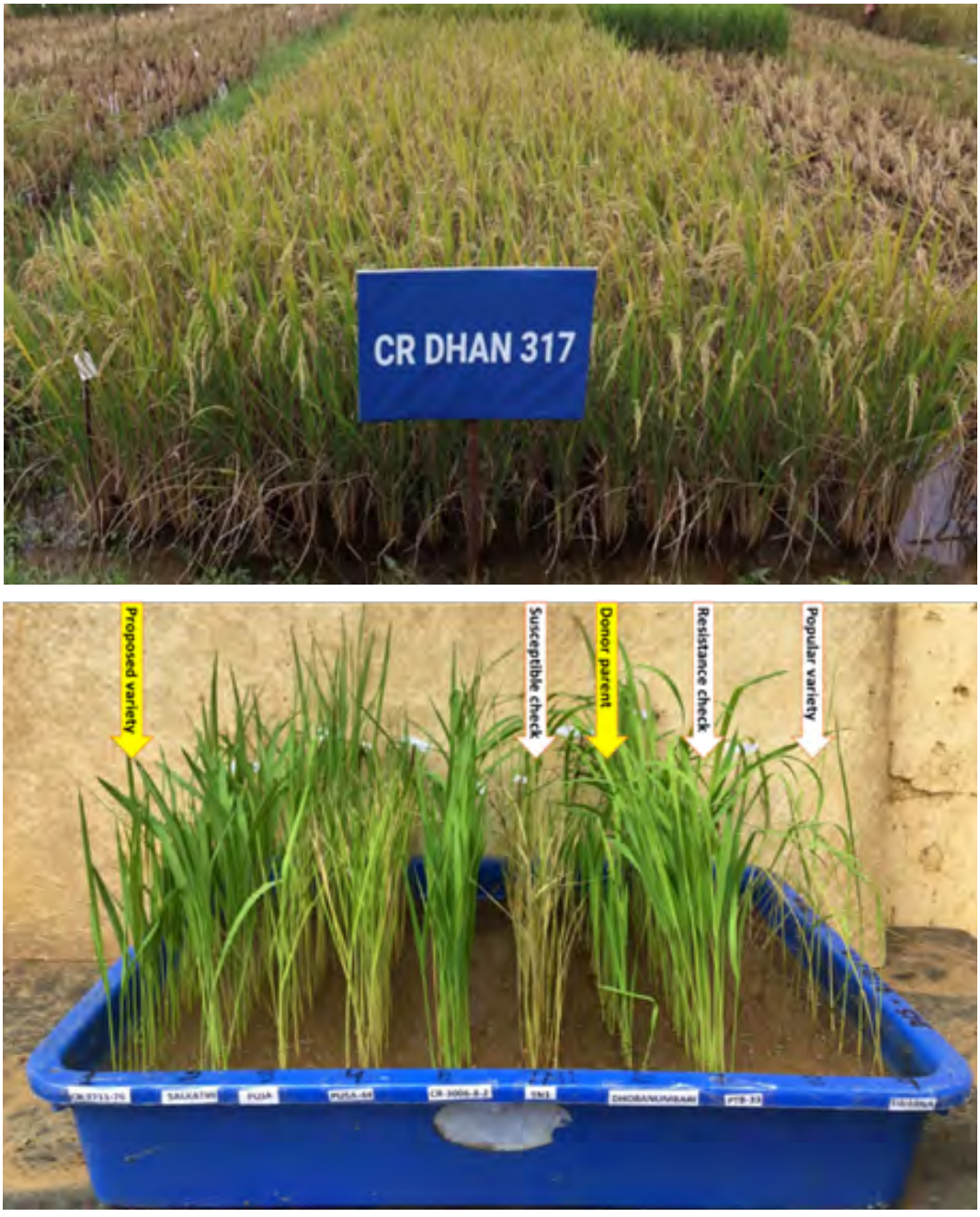

Figure 11. Net house screening of CR 2711-76 against BPH along with parents (Tapaswini and Dhobanumberi), resistance check (PTB33), susceptible check (TN1) and other popular varieties

also identified from that interval and nearby flanking regions of chromosome 4 by screening 25 more reported markers. For background selection, genome-wide distributed markers from all chromosomes were screened, and 107 polymorphic markers were identified between Naveen and CR 3006-8-2. Background selection was carried out through a reduction-based approach (Ellur et al., 2016). The flanking markers for *qBph4.3* and *qBph4.4* (Mohanty et al., 2017) were used for foreground selection during the advancement of progeny lines from BC_1F_1 to BC_2F_1 from the cross Naveen/CR-3006-8-2. Till BC_1F_1, only the lines carrying the entire region of the two QTLs were chosen and further backcrossed with the recurrent parent. In BC_2F_1, the recombinants within QTL intervals were also selected. In BC_2F_2, homozygous NILs for both QTLs and recombinants between and within QTLs were identified and advanced further. Background selection was performed by 107 SSR markers distributed over the 12 chromosomes. Rigorous phenotypic selection for recurrent parent type was performed till BC_2F_5 and seeds were bulked in BC_2F_6. The detailed breeding scheme have been represented in Figure 12.

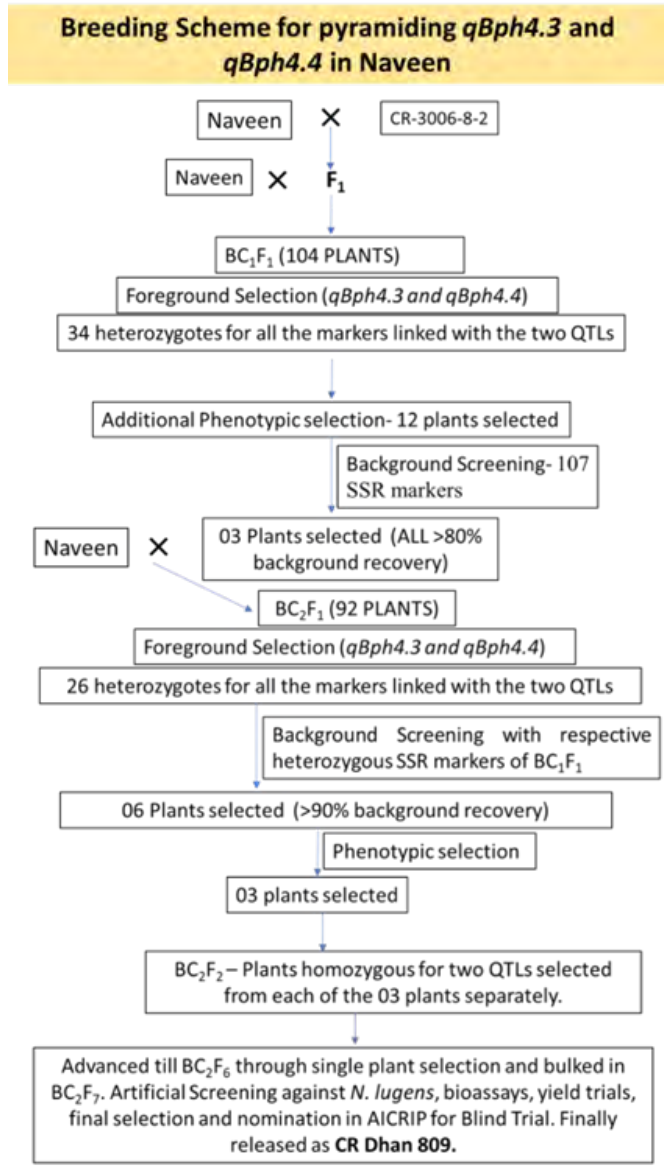

Figure 12. Breeding scheme followed for developing BPH resistant NILs of Naveen

6.3.2. Identification best NILs and subsequent release of cultivars

In the case of Naveen, three NILs (CR 4331-74-2-2-1, CR-4331-84-3-2-1 and CR 4331-85-1-2-1) were identified and tested in AICRIP. The entry CR 4331-85-1-2-1 (IET 29203) showed superior performance only in Odisha in terms of comparable yield level with Naveen and was released as variety CR Dhan 805 only for Odisha state (Figure 13).

Figure 13. Brown Planthopper-resistant variety CR Dhan 805

Among the entries, the genotype CR-4331-84-3-2-1 (IET 30282) (Figure 14) showed superior performance in terms of grain yield across all six states (Odisha, Bihar, Jharkhand, West Bengal, Assam and Tripura) where Naveen is grown. During all the years of testing, the genotype also recorded a higher level of resistance than Naveen, besides comparable grain quality. Based on the performance, the entry was identified for release as CR Dhan 809 for these six states by the Varietal Identification Committee (VIC) of AICRIP in April 2024 and subsequently released and notified by the Central Sub-Committee on Crop Standards, Notification and Release of varieties. Compared to the 5069 kg/ha yield of Naveen, CR Dhan 809 recorded a grain yield of 5095 kg/ha across the six states over the years. This confirmed that the introgression of the QTLs from Salkathi didn't cause a yield

penalty. In terms of grain quality, CR Dhan 809 showed short bold grains with 59.4% head rice recovery (HRR), 24.3% amylose in its grains, gel consistency (GC) value of 36.5 and alkali spreading value (ASV) of 3.9. These results indicated similar yield levels and grain quality of CR Dhan 809 when compared with its recurrent parent Naveen. Besides yield and grain quality, CR Dhan 809 showed same maturity duration (125 days) and similar plant height like Naveen.

Figure 14. Representative plants of Naveen (recurrent parent), CR-3006-8-2 (donor) and CR Dhan 809 (Naveen-BPH-NIL)

A substantially enhanced level of resistance against BPH was recorded in CR Dhan 809 when compared with Naveen under AICRIP trials. During 2022, data was recorded for hopper burn percentage in CR Dhan 809 when compared to Naveen. Compared to the 100% hopper burn recorded in Naveen, only 14.80% was recorded in CR Dhan 809. BPH screening of CR Dhan 809 vis-à-vis Naveen was also carried out for three years (2021, 2022 and 2023) at multiple test sites through artificial screenings and was scored in terms of Damage Score (DS). The performance of CR Dhan 809 over three years confirmed its superiority against the existing biotype across India (Table 8, Figure 15).

Table 8. Comparative damage score (DS) of CR Dhan 809 Vs Naveen against BPH in AICRIP multilocation trials over years

	Damage score (DS) against BPH		
Genotype	2021	2022	2023
CR Dhan 809	2.43	3.55	4.22
Naveen	8.20	7.67	8.37

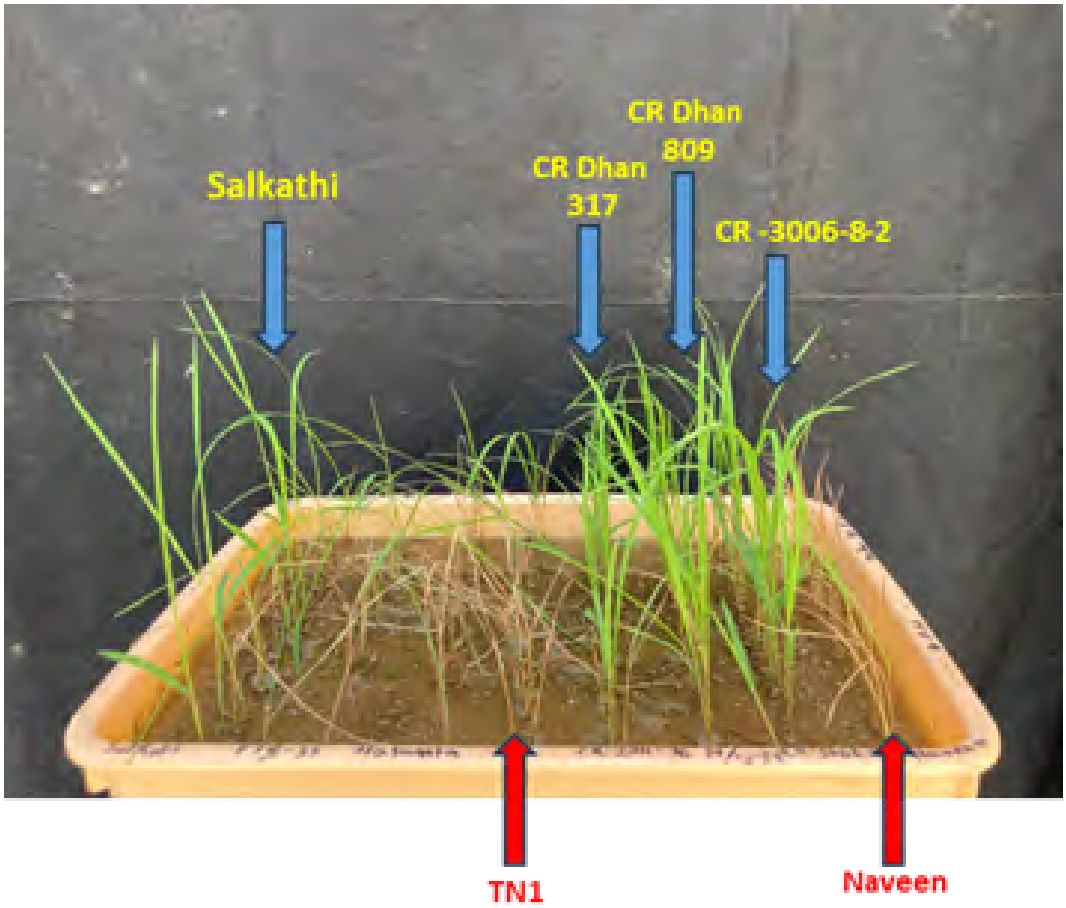

Figure 15. BPH resistance recorded in CR Dhan 809, pre-breeding line CR-3006-8-2 (donor line), landrace Salkathi and another resistant variety CR Dhan 317 when compared to susceptible reaction of TN1 and recurrent parent Naveen under artificial screening again BPH.

6.4. BPH-resistant NILs of Pooja

The same strategy of marker-assisted backcross breeding followed in the case of Naveen was adopted in the case of Pooja. However, due to the photosensitive nature of the variety, only one season could be advanced in a year. Currently, Pooja has ten BPH-resistant NILs available at NRRI. Based on morphological similarity with the recurrent parent, comparable yield and grain quality, one NIL (CR 4696-2-15-32-82) has been nominated in the AICRP trial (Figure 16).

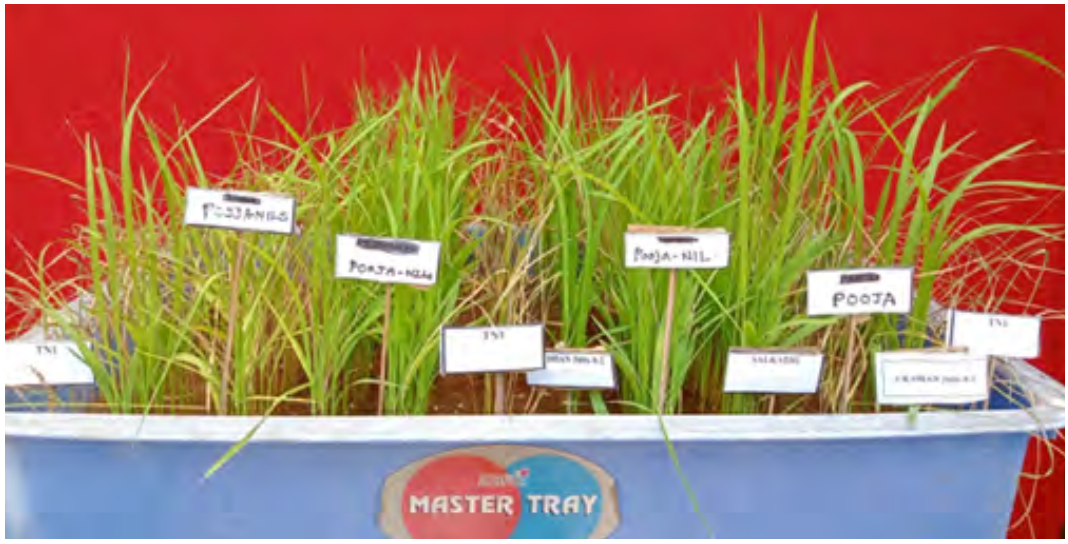

Figure 16. NILs of Pooja carrying BPH resistance QTLs of Salkathi showing resistance against BPH in artificial screening compared to susceptible reaction of Pooja

7. Management strategies for brown planthopper

Monitoring and surveillance

- Surveillance and monitoring of the insect are prime necessities to carry out effective management operations. Agro-advisory services are being issued by ICAR institutes/ SAUs at fortnightly intervals on a regular basis from 1st week of September. Hence, monitoring should start from 1st week of September. The basal part of some rice plants are to be disturbed mildly with a stick so that BPH jumps to standing water from which the economic threshold level or ETL of the insect can be known (5-10 insect/hill).

- Use a light trap per acre and a yellow sticky trap for monitoring. NRRI developed a Solar 24 x 7 Insect trap, which may be recommended as 1 trap per ha for monitoring purposes (Mohapatra, 2024). In addition, the Alternate Energy Light Trap (an NRRI-patented product) can also be deployed in the field to monitor BPH incidence.

Cultural Methods

- Irrigation by alternate drying and wetting.
- Draining out water from the insect-infested fields.
- Judicious use of fertilizers; Split application of nitrogenous fertilizer along with appropriate dose of potassium fertilizer.
- Alley planting (leaving two lines) after each of the 8 lines in endemic areas helps in minimizing the population.
- Avoid close planting and follow split application of N fertilizer.

Resistant/tolerant varieties

- Though not developed for targeted breeding for BPH, some of the varieties tested under AICRIP National Screening Nursery Trial showed some degree of resistance to BPH in the following varieties *viz*., Udaya, Daya, Lalt, Sakthiman for Odisha; Jyoti, Bhadra, Karthika, Makon, Remya, Kanaka for Kerala, Bharatidasan for Pondicherry, Sonasali, Nagarjuna, Vajram, Krishnaveni for Andhra Pradesh and Mansarovar for Central Release, etc. These varieties should be grown suitably in BPH endemic areas of different states.

Predators/parasitoids

- In-situ conservation of natural enemies, especially hunting spiders, *Lycosa pseudoannulata* and *Argiope* Sp., is very effective against planthoppers.
- Another important egg-feeding predator is the mirid bug, *Cyrtorhinus lividipennis*.
- Provide refuge like straw bundles having charged with spiders to help in build up spider population and to provide perch for birds.

Botanical Control

- When the pest population is about 3-5, insect/hill botanicals may be preferred.
- A foliar spray of Neem oil at 5-8 ml/L with 0.5 ml liquid detergent will kill the insects

and significantly reduce the egg-laying capacity of the females, thereby reducing the population's spread.

- A foliar spray of water pepper leaf at 20 gm/L with 0.5 ml liquid detergent as an ITK can effectively manage BPH.

Chemical Control

- Insecticides with high efficacy at low doses, such as Thiamethoxam 25 WG @ 2g/10 lit, Imidacloprid 17.8 SL @ 2.5 ml/10 lit, Flunicamide 50WG @ 3g / 10 lit, Dinotefuran 20SG @ 3 g/10 lit, or Clothianidin, can be used at 20-22 g/ha, Triflumezopyrim 10% SC @ 235 ml/ha or Pymetrozine 50 WG @ 6 g/10 lit of water.
- Chemical control should be used as a last resort. Proper care should be taken at the time of application, including wearing face and hand masks and during the safe disposal of pesticide containers.
- Spraying should be directed towards the basal portion of the plants. Repeat the application if the hopper population persists more than a week after the first application.

7.1. Precautionary measures required in the BPH endemic areas to avoid the outbreak

- Since timely monitoring of the pest is essential to detect the population at the proper stage of the crop, farmers must be made aware of ETL and proper management strategies through training, advisory services through the Institute Agro-Advisory service, technical bulletins (Hindi, English and Odia), Diagnostic pocket diaries, the mobile app "riceXpert," newspapers, television and interviews.
- In endemic areas, Swarna should be replaced by other suitable varieties having tolerance/resistance to BPH.
- Balance fertilizer application, particularly N & K should be followed.
- Awareness must be created to avoid staggered planting. If this is followed, community-based control measures should be taken to avoid pest dispersal.
- Trainer training programs must be organized at regular intervals at NRRI and other ICAR institutes/SAUs for VAWs, AOs, and other workers related to the subject.
- Extensive extension was to be undertaken to introduce highly resistant, high-yielding rice genotypes to the area.
- A rice-based cropping system is to be introduced to break the insect cycle in the rice-rice cultivation system.

- Don't apply nitrogenous fertilizer if the crop is in the flowering or milky stage; this will facilitate the BPH infestation.
- Robust inspection of pesticide quality should be carried out at regular intervals, and stringent action should be taken to avoid the use of spurious pesticides.
- Detailed research work to be carried out in the BPH endemic areas on any changes in insect pest appearance, biotype development and virulence against insecticide, which is very essential to avoid such havoc in the future.
- Burning affected crops would lead to rapid dispersal of the pest to unaffected paddy fields. We also requested that they refrain from burning affected crops.
- Resistant lines from ICAR institutes/SAUs should be screened in BPH-endemic areas, and the resistant lines should be included in the breeding program, either conventionally or through MAS.

7.2. Do's

- Apply only the recommended dose of insecticide.
- Drain the stagnant water from the BPH-infested field and irrigate if required
- Make an alley after every 8 rows or at 6 ft intervals to facilitate spraying and exposure to sunlight.
- Use 200 liters of spray solution for the power sprayer and 500 liters for the knapsack sprayer for a hectare of land.
- Strictly follow the protective measures during the spraying of insecticides

7.3. Don'ts

- Don't spray the same type of insecticides repeatedly
- If the crop is in the maturity stage, don't apply insecticides
- Don't mix two or more pesticides
- Don't use insecticides or kerosene or phenyl, which are not recommended
- In BPH-infested areas, don't apply nitrogenous fertilizers
- Don't burn the crop as it will lead to the following deleterious effect
  - Winged form of female BPH will migrate from the burnt field to other fields and infest the crop.
  - Beneficial insects like mirid bugs, spiders, etc., will be killed, which will result in a flare-up of more BPH attacks in the next season's rice crop.

8. Upscaling in the farmers' field

BPH outbreaks frequently occur in Odisha and other parts of the country, and farmers suffer huge losses; hence, BPH-resistant varieties have been developed. CR Dhan 317, suitable for the irrigated ecosystems, is a derivative line from the cross of Tapaswini and Dhobanumberi. BPH nymphs could not suck the phloem sap from this variety and could not complete its lifecycle. Antibiosis mechanism of resistance has been recorded in this variety as it contains *BPH31* gene. Further, the trial was conducted on 66 farmers' fields in Odisha, particularly in the endemic area of BPH, where this variety exhibited resistance against BPH with an average yield of 5.45 t/ha, along with resistance reaction to bacterial leaf blight and sheath blight. Likewise, CR Dhan 805, suitable for both rainfed and irrigated ecosystems, is a derivative line from the cross of Naveen x CR-3006-8-2 (Salkathi-derived line). BPH nymphs could not suck the phloem sap from this variety and antixenosis and antibiosis mechanisms of resistance have been recorded in this variety. Further, the trial was conducted on 50 farmers' fields in Odisha, particularly in the endemic area of BPH, where this variety produced an average of 6.40 t/ha yield with BPH resistance. A front-line demonstration was conducted in the farmer's field to spread the variety and detail provided in Table 9. A total of > 8 tonnes of seeds of these varieties has been supplied to farmers, KVK, and National partners till now.

Table 9. Number of front-line demonstrations conducted at farmers' field

Sl No	Name of the project	No. of farmers received BPH-resistant varieties			
		General/OBC	SC	ST	Total
1	Popularization of BPH resistant Rice varieties for the upliftment of Odisha farmers' income	412	50	175	637
2	TSP Program	-	-	170	170
3	SCSP Program	-	200	-	200

9. Way Ahead

Biotechnological tools like gene pyramiding, transgenic approaches, marker-aided selection, gene editing, etc. have been exclusively exploited to impart host plant resistance to biotic stresses. The following area of research needs to be strengthened for BPH-resistant variety development

- Concerted efforts are needed for the identification of new sources of BPH resistance.
- New knowledge of ecology and migration studies on BPH will help to decipher the infestation routes of this pest.
- Research on the genetics of the insect may provide insights to develop novel plant protection technologies.
- Database creation and utilization, as well as long-term storage of BPH-resistant donors.
- Identification and fine mapping of novel QTLs/genes, use of gene editing technology to validate functions of novel QTLs/genes, identification of superior haplotypes, pyramiding of multiple superior haplotypes of effective QTLs/genes in different popular susceptible rice varieties to develop durable BPH resistant varieties.
- Cloning of these QTLs/genes to understand molecular mechanisms of BPH resistance and to develop better control strategies.
- Further, emphasis should be given to upscaling seed production and distribution, popularization through trails, awareness programs for different aspects of BPH management.

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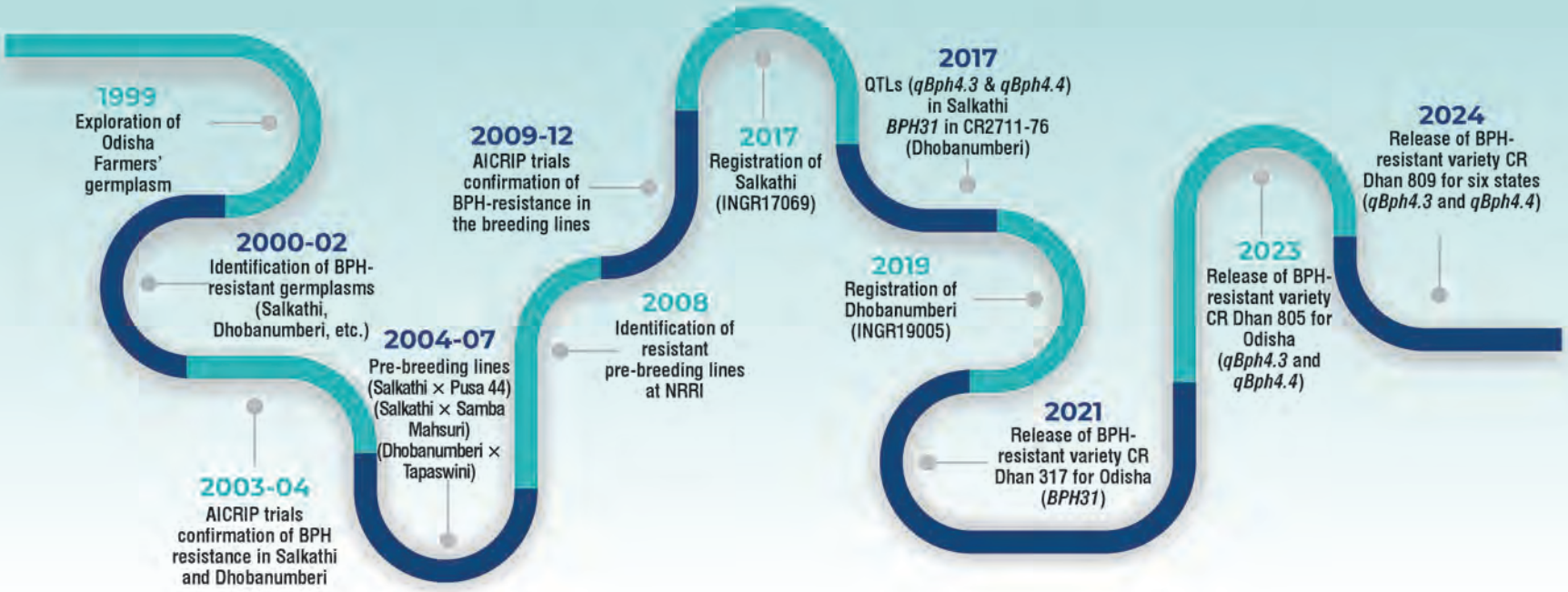
ROADMAP

BPH Resistant Rice: A Journey from landraces to varieties



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