Fine-tuning roles of Osa-miR159a in rice immunity against Magnaporthe oryzae and development

Jin-Feng Chen
Sichuan Agricultural University - Chengdu Campus

Zhi-Xue Zhao
Rice Research Institute and key Lab for Major Crop Disease, Sichuan Agricultural University

Yan Li
Sichuan Agricultural University - Chengdu Campus

Ting-Ting Li
Sichuan Agricultural University - Chengdu Campus

Yong Zhu
Sichuan Agricultural University - Chengdu Campus

Xue-Mei Yang
Sichuan Agricultural University - Chengdu Campus

Shi-Xin Zhou
Sichuan Agricultural University - Chengdu Campus

He Wang
Sichuan Agricultural University - Chengdu Campus

Ji-Qun Zhao
Sichuan Agricultural University - Chengdu Campus

Mei Pu
Sichuan Agricultural University - Chengdu Campus

Hui Feng
Sichuan Agricultural University - Chengdu Campus

Jing Fan
Sichuan Agricultural University - Chengdu Campus

Ji-Wei Zhang
Sichuan Agricultural University - Chengdu Campus

Yan-Yan Hang
Sichuan Agricultural University - Chengdu Campus

Wenming Wang (j316wenmingwang@163.com)
Sichuan Agricultural University - Chengdu Campus

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Abstract

Background: Rice blast caused by Magnaporthe oryzae is one of the most destructive diseases of rice. An increasing number of microRNAs (miRNAs) have been reported to fine-tune rice immunity against M. oryzae and coordinate with growth and development.

Results: Here, we showed that rice microRNA159a (Osa-miR159a) played a positive role in rice resistance to M. oryzae. The expression of Osa-miR159a was suppressed in a susceptible accession at 12, 24, and 48 hours post-inoculation (hpi); it was upregulated in a resistant accession of M. oryzae at 24 hpi. The transgenic rice lines overexpressing Osa-miR159a were highly resistant to M. oryzae. In contrast, the transgenic lines expressing a short tandem target mimic (STTM) to block Osa-miR159a showed enhanced susceptibility. Knockout mutations of the target genes of Osa-miR159a, including OsGAMYB, OsGAMYBL, and OsZF, led to resistance to M. oryzae. Alteration of the expression of Osa-miR159a impacted yield traits including pollen and grain development.

Conclusions: Our results indicated that Osa-miR159a positively regulated rice immunity against M. oryzae by downregulating its target genes. Proper expression of Osa-miR159a was critical for coordinating rice blast resistance with grain development.

Background

Plant microRNAs (miRNAs) act as fine-tuning regulators and play regulatory roles in gene expression via cleavage, translational inhibition, or DNA methylation of target sites with sequences complementary to the miRNAs (Song et al., 2019). To date, more than 38,000 mature miRNAs have been reported in miRBase (http://www.mirbase.org/). Among them, 757 mature miRNAs have been identified in rice.

miRNAs play major roles in many biological processes, including functions related to response to biotic and abiotic stressors (Jones-Rhoades et al., 2006; Miura et al., 2010; Yan et al., 2016; Li et al., 2019b). Functional studies of many miRNAs have been done on Arabidopsis and rice. For example, knockout of miR396ef results in increased grain yield in rice via increasing grain size and panicle branching due to disinhibition of the expression of OsGRF4 and OsGRF6, which are the target genes of miR396 (Zhang et al., 2019; Miao et al., 2020). The overexpression of miR1873 results in defects in yield traits by repressing its target gene LOC_Os05g01790 (Zhou et al., 2020). miR535 is highly expressed in rice panicles. Enhanced accumulation of miR535 reduces plant height, modifies panicle architecture, and increases the grain length by regulating OsSPLs (Sun et al., 2019). miR176 regulates stamen and gynoecium development in immature flowers by regulating the target genes ARF6 and ARF8 in Arabidopsis (Wu et al., 2006). Increasing evidence shows that miRNAs are involved in rice immunity against Magnaporthe oryzae. For example, overexpression of miR1873 enhanced the susceptibility of rice to M. oryzae by regulating its target gene LOC_Os05g01790 (Zhou et al., 2020). In addition, miR396, miR159, miR164a, miR319b, and miR167d negatively regulate immunity against M. oryzae in rice (Li, Y et al., 2017; Wang et al., 2018; Zhang et al., 2018; Chandran et al., 2019; Zhao et al., 2019), whereas miR398b, miR160a, miR166k-miR166h, miR7695, and miR162a positively regulate the response against M. oryzae in rice (Achard et al., 2004; Salvador-Guirao et al., 2018; Li et al., 2019a; Li et al., 2019b; Quoc et al., 2019; Li, X-P et al., 2020).

The highly conserved and abundant 21 nucleotide (nt) miRNAs, miR159 and miR319, share a sequence identity of 17 out of 21 nt matching with that of Arabidopsis (Palatnik et al., 2007). However, miR159 and miR319 function differently through distinct target genes. miR319 targets PROLIFERATING CELL NUCLEAR ANTIGEN BINDING FACTOR (TCP) transcription factor genes, which control leaf shape (Schwab et al., 2005; Palatnik et al., 2007), while miR159 targets a family of genes encoding R2R3 MYB transcription factors, which are referred to as GAMYBs or GAMYB-likes (GAMYBLs), and function in flowering and male fertility (Millar et al., 2019). The miR159-GAMYB regulatory module has been identified in major land plants, including Arabidopsis and rice. This module has been reported to act in growth and development. In Arabidopsis, miR159 suppresses the expression of MYB33 and MYB65 to regulate plant growth and development. miR159a/miR159b (miR159ab) double mutant displays severe growth and developmental defects including curled rosette leaves and stunted plant height (Allen et al., 2007). These phenotypes may be due to the failure to suppress the expression of MYB33 and MYB65 by miR159 (Allen et al., 2007; Alonso-Perera et al., 2010). Also, up-regulation of miR159 impacts another development and delays flowering. Moreover, miR159 plays a crucial role in pollen fertility, and pollen-carried miR159 abolishes the expression of MYB33 and MYB65 in the central cell after fertilization, promoting endosperm nuclear division and seed development (Zhao et al., 2018). miR159 regulates flowering time and development during the short-day photoperiod by directly cleaving the miRNA of GAMYB-related genes that encode proteins involved in GA-promoted activation of LEAFY (Achard et al., 2004). In addition, miR159-MYB33 functions as a modifier of vegetative phase change in Arabidopsis (Guo et al., 2017).

The rice genome contains six Osa-miR159 genes generating five mature isoforms: Osa-miR159a, Osa-miR159b, Osa-miR159c, Osa-miR159d, Osa-miR159e, and Osa-miR159f. These isoforms mediate mRNA cleavage of three genes, GAMYB (LOC_Os01g59660), GAMYBL (LOC_Os06g04330), and ZF (encoding a C3HC4-type domain-containing zinc finger protein, LOC_Os10g05230). GAMYB has been shown to function in rice development. For example, miR159-GAMYB modulates the expression of gibberellic acid (GA)/abscisic acid (ABA)-related genes to maintain the energy supply and enhance developmental processes in Wuxiang S, a photo-thermosensitive genic male sterile rice line (Zhang et al., 2016a). In addition, a few studies show that miR159 functions in plant immunity. For example, in cotton, miR159 and miR166 are increased in response to infection by Verticillium dahliae, and are exported to the fungal hyphae to silence the target genes Ca^2+-dependent cysteine protease (CIP1) and an isoroticchioemnin C-15 hydroxylase (HiC-15), which are essential for fungal virulence (Zhang et al., 2016b). In Lilium regale, ire-miR159a positively regulates the plant’s resistance to grey mold caused by Botrytis elliptica by repressing the expression of its target gene LeGAMYB (Gao et al., 2020). In a previous study, we found that Osa-miR159a was differentially accumulated in susceptible and resistant accessions of rice (Li et al., 2014). However, its function in rice immunity has not been characterized.

In this study, we further functionally characterized Osa-miR159a. To accomplish this, we obtained the transgenic lines overexpressing Osa-miR159a (OX159) and the suppressed expression of Osa-miR159a (STTM159) through short tandem target mimic (STTM), which is an effective method to block mature miRNA binding to target sites of the target genes (Yan et al., 2012). In addition, we also constructed the knockout transgenic lines of GAMYB, GAMYBL, and ZF using the CRISPR/Cas9 method. Then, these transgenic lines were subjected to a M. oryzae disease assay and the phenotypic assay. We found that Osa-miR159a
acts as a positive regulator in rice resistance to *M. oryzae* by suppressing GAMYB, GAMYBL, and ZF. It also impacted reproductive development in rice. Therefore, proper accumulation of *Osa-miR159a* was necessary to fine-tune the development and resistance to *M. oryzae* in rice.

**Results**

*Osa-miR159a is Responsive to *M. oryzae* Infection*

Previously, the expression of *Osa-miR159a* was reported to be responsive to *M. oryzae* or its elicitors (Li et al., 2014; Li, Z-Y et al., 2016; Li et al., 2019b). To confirm this conclusion, we examined its expression pattern in susceptible and resistant accessions of rice after inoculation of *M. oryzae* at the three-leaf seedling stage. The universally susceptible accession Lijiangxin Tuan Heigu (LTH) showed a severe disease phenotype, whereas the accession (IRBLkm-Ts) that contains the gene *Pikm*, which confers *M. oryzae* resistance displayed resistance (Fig. 1a). Compared with mock inoculation, *M. oryzae* infection resulted in decreased accumulation of *Osa-miR159a* at 12, 24, and 48 hours post-inoculation (hpi) in LTH (Fig. 1b). In contrast, *Osa-miR159a* was significantly upregulated at 24 hpi in IRBLkm-Ts (Fig. 1b), although it was also significantly decreased at 48 hpi. These data indicated that the response of *Osa-miR159a* to *M. oryzae* infection was different in the susceptible and resistant accessions. Therefore, *Osa-miR159a* may play a role in rice immunity against *M. oryzae*.

*Osa-miR159a Positively Regulates Rice Resistance to *M. oryzae***

To explore how *Osa-miR159a* acts in the interaction between rice and *M. oryzae*, we made a construct overexpressing *Osa-miR159a* (OX159) and introduced the construct into Nipponbare (NPB), generating 24 independent transgenic lines, out of which we chose two lines that showed high *Osa-miR159a* accumulation for further investigation (Fig. 2a). We made a construct expressing STTM of *Osa-miR159a* (STTM159) and introduced it into NPB, which may prevent *Osa-miR159a* from binding to its target sites (Franco-Zorrilla et al., 2007; Todesco et al., 2010). We also selected two independent transgenic lines that showed a significant reduction of *Osa-miR159a* accumulation for further investigation (Fig. 2a). Then we conducted blast disease assays by punch- or spray-inoculation of the *M. oryzae* strain G2B. We found that OX159 lines generated significantly smaller disease lesions than NPB harboring an empty vector (EV) (Fig. 2b and Fig. S1a). Consistently, the lesions from OX159 lines contained significantly less fungal mass and shorter lesion length than the control at 5 days post-inoculation (Fig. 2c, d and Fig. S1b). In contrast, STTM159 lines generated significantly larger disease lesions than that of the control (Fig. 2e and Fig. S2a), and the lesions from STTM159 lines contained significantly more fungal mass and longer lesions than the control at five days post-inoculation (Fig. 2f, g and Fig. S2b, c). These data indicated that *Osa-miR159a* positively regulated the resistance of rice to *M. oryzae*.

Next, we exploited the GFP-tagged strain G2B to observe the infection process in sheath cells using laser scanning confocal microscopy. Compared with the control, our observation found that the infection progress was delayed in OX159 (Fig. S1c, d), but accelerated in STTM159 (Fig. S2d, e). At 24 hpi and 36 hpi, the percentages of invasive hyphae were much lower in OX159 (Fig. S1c, d) compared with the control; however, the percentages of invasive hyphae were greater in STTM159 (Fig. S2d, e). These results indicated that overexpressing *Osa-miR159a* delayed infection, whereas blocking *Osa-miR159a* facilitated *M. oryzae* infection.

To explain why *Osa-miR159a* positively regulated resistance to *M. oryzae*, we used RT-qPCR to examine the expressions of some marker genes, including OsNAC4, OsPR10b (*Pathogenesis-Related* 1b) and OsJAMYB, acting in immune responses after infection with *M. oryzae* (Park et al., 2012; Pan et al., 2014). The expression of OsNAC4 was higher in OX159 than in the control at 6 and 12 hpi (Fig. S1e), whereas it was lower in STTM159 than in the control at 6 and 24 hpi (Fig. S2f). The expression of OsPR10b was higher in OX159 than in the control at 6 hpi (Fig. S1f); it was lower in STTM159 than in the control at 0, 12, and 24 hpi (Fig. S2g). The expression of OsJAMYB was higher in OX159 than in the control at 6 and 12 hpi (Fig. S1g), while it was lower in STTM159 than in the control at 6 and 12 hpi (Fig. S2h). These data indicated that *Osa-miR159a* activated defense-related genes, positively regulating rice resistance to *M. oryzae*.

**Alteration of *Osa-miR159a* Accumulation Leads to Developmental Defects**

In addition to the resistance conferred by *Osa-miR159a* in rice against *M. oryzae*, we found that both OX159 and STTM159 showed some altered development and yield traits. All the OX159 and STTM159 transgenic lines were shorter than the control (Fig. 3a, b and Table 1), with STTM159 lines significantly shorter than OX159 lines and the control (Fig. 3b and Table 1). Both OX159 and STTM159 had a lower yield (Table 1). The OX159 lines were sterile and had only a few filled grains on the panicle, leading to straight panicles at the mature stage (Fig. 3a, c and Table 1). The stamen development was deficient in OX159 lines (Fig. 3e, f). In comparison with the control, which had yellowish anthers containing fertile pollen indicated by starch-staining, anthers from OX159 were pale with sterile pollen lacking starch (Fig. 3g). In addition, grains from OX159 lines lacked starch accumulation, although the ovary grew to a size comparable to that of the control (Fig. 3h, i, l, m and Table 1). However, STTM159 showed smaller panicles than that of the control, but the starch accumulation in the grain was normal (Fig. 3d, j, k). STTM159 was also observed to be less productive than the control (Table 1). The grain width of STTM159 was the same as the control, whereas the grain length was shorter than the control (Fig. 3l, m and Table 1). These results indicated that the alteration of *Osa-miR159a* expression led to defects in growth and development, particularly in pollen and grain development.

**Alteration of *Osa-miR159a* Expression Impacts the Expression of Its Target Genes That are Responsive to *M. oryzae***

Six *Osa-miR159* loci in rice generate five mature isomers that share 18 central nucleotides (Fig. S3a). Among them, *Osa-miR159a/b* targeted two confirmed genes, namely, *OsGAMYB* (*LOC_Os01g59660*) and *OsGAMYBL* (*LOC_Os06g40330*) (Li, H et al., 2016), and one predicted gene, *LOC_Os10g05230* (encoding a C3HC4-type domain-containing zinc finger protein, herein designated *OzsF*) (Khan et al., 2017). The target sites in *OsGAMYB* and *OsGAMYBL* were in the coding region, whereas the target site was in a 5' untranslated region (UTR) of *OzsF* (Fig. S3b). To examine how the expression of these genes was impacted by the alteration of *Osa-miR159a* expression in OX159 and STTM159, we performed a RT-qPCR analysis. As expected, the expression of all three genes was significantly less in OX159 than in the control (Fig. S3c). In contrast, the expression of all these genes was more in STTM159 than in the control (Fig. S3c).
These data indicated that the overexpression of *Osa-miR159a* significantly suppressed the expression of its target genes, and the STTM of *Osa-miR159a* prevented the suppression of *Osa-miR159a* on the expression of its target genes.

Next, we examined the expression of *OsGAMYB*, *OsGAMYBL*, and *OsZF* in LTH and IRBLkm-Ts after infection with *M. oryzae*. The expression of *OsGAMYB* and *OsGAMYBL* was constitutively higher in IRBLkm-Ts than in LTH (0 hpi in Fig. 4a, b). After *M. oryzae* infection, *OsGAMYB* was significantly up-regulated at 12 hpi and 24 hpi, and down-regulated at 48 hpi in LTH. In IRBLkm-Ts, *OsGAMYB* was up-regulated at 12 hpi, but significantly down-regulated at 24 hpi and 48 hpi (Fig. 4a). The expression of *OsGAMYBL* was relatively stable in both LTH and IRBLkm-Ts with a significant up-regulation at 24 hpi in IRBLkm-Ts (Fig. 4b).

*OsZF* was significantly upregulated at 12 hpi and 24 hpi, but decreased to the level of background expression at 48 hpi in both LTH and IRBLkm-Ts (Fig. 4c). These expression patterns indicated that they were responsive to the infection of *M. oryzae* in both susceptible and resistant accessions.

**Knockout of OsGAMYB, OsGAMYBL, and OsZF Leads to Enhanced Resistance to M. oryzae**

To investigate the function of *OsGAMYB*, *OsGAMYBL*, and *OsZF*, we obtained mutants using CRISPR/Cas9 DNA editing. We identified two independent mutants for *OsGAMYB*, *OsZF*, and *OsGAMYBL*. Among them, *gamyb*-1 carried a 1-bp insertion resulting in an early stop codon after aa 325 (Fig. 5a). *gamyb*-2 carried a 1-bp deletion resulting in an early stop codon after aa 311 (Fig. 5a); *zf-4* carried a 1-bp insertion resulting in an early stop codon after aa 42 (Fig. 5b). The *zf-8* had a 1-bp deletion resulting in an early stop after aa 32 (Fig. 5b); *gamyb*-5 carried a 2-bp deletion resulting in an early stop codon after aa 127 (Fig. 5c). The *gamyb*-10 had a 1-bp insertion resulting in an early stop codon after aa 128 (Fig. 5c). We conducted a *M. oryzae* assay via punch-inoculation. All the knockout lines significantly decreased the size of *M. oryzae* lesions that contained significantly lower fungal mass and shorter lesions than that of the control (Fig. 5 d-f). Specifically, *gamyb* mutants were especially resistant than *gamyb* and *zf* mutants, indicating that *OsGAMYBL* has the most important role in disease resistance. Together, these results indicated that *OsGAMYB*, *OsGAMYBL*, and *OsZF* contributed to *Osa-miR159a*-mediated regulation of rice resistance to *M. oryzae*. However, based on previous studies, loss of function mutations of *OsGAMYB* resulted in shortened internodes and defects in floral organ development (Kaneko et al., 2004); loss function of *OsGAMYBL* also contribute to these phenotypes (Tsujii et al., 2006). Similarly, we found that loss of function mutations of *OsGAMYB* or *OsGAMYBL* cause defective rice development (data not shown), especially in relation to pollen development. However, the phenotype of *zf* mutants was very similar to that of the wild type, except for the slightly reduced height of the *zf* mutants (Fig. S4a), but not in 1,000-grain weight (Fig. S4b). Together with the resistance phenotype, the editing of *OsZF* may have a potential application in rice breeding.

**Discussion**

miRNAs act as important regulators in plant growth, development, and host-pathogen interactions (Jones-Rhoades et al., 2006; Baldrich & Segundo, 2016). Some miRNAs have been identified to be involved in fine-tuning rice resistance to *M. oryzae* and yield traits. For example, high accumulation of *Osa-miR1873* results in defects in growth and yield-related traits, and also increases susceptibility to *M. oryzae* (Zhou et al., 2020). Here, we described *Osa-miR159a*, which regulates multiple growth and yield traits, as a new positive regulator in rice resistance to *M. oryzae*. First, high accumulation of *Osa-miR159a* resulted in enhanced resistance to *M. oryzae*, which was associated with an increase in the defense response, i.e., high expression of defense-related genes (Fig. 2b-d and Fig. S1). In addition, the transgenic lines overexpressing *Osa-miR159a* showed developmental defects such as pollen sterility and grain-filling (Fig. 3a, c). However, blocking *Osa-miR159a* by STTM resulted in increased susceptibility to *M. oryzae* (Fig. 2e-g and Fig. S2). Developmental defects were also observed in STTM159 transgenic lines including shorter plants and reduced grain length (Fig. 3b, d, m). Consistent with the *M. oryzae* disease phenotypes in Ox159 and STTM159, the *OsGAMYB*, *OsGAMYBL*, and *OsZF* knockout lines exhibited enhanced resistance to *M. oryzae*. Therefore, *Osa-miR159a* has multiple functions in rice resistance to *M. oryzae* and rice development.

*miR159a* is a conserved miRNA that represses the expression of *GAMYB*-like genes, which encode MYB domain transcription factors (Alonso-Peral et al., 2010). Proper expression of *GAMYB* and *GAMYBL* are important for rice development. GAMYB acts as a positive transcriptional regulator of GA-dependent α-amylase expression and also has important roles in floral organ development and pollen development (Kaneko et al., 2004). Here, we demonstrated that suppressing GAMYB by overexpressing *Osa-miR159a* resulted in sterile pollen lacking starch and failure of the grain to accumulate starch (Fig. 3e-i); however, the grain length was slightly larger than that of the wild type (Table 1). In addition, the uninhibited expression of GAMYB by overexpressing STTM159 also resulted in slightly shorter grains (Fig. 3m and Table 1). These results indicated that GAMYB was crucial for grain development. We observed that enhanced or decreased expression of *Osa-miR159a* also impacted plant height (Fig. 3a, b and Table 1). Previous studies reported that loss of function mutations of *OsGAMYB* results in shortened internodes; *OsGAMYBL* contributes to this phenotype (Kaneko et al., 2004; Tsujii et al., 2006), indicating that *OsGAMYB* and *OsGAMYBL* played a role in the height of rice plants. However, *zf* mutants showed slightly reduced height without other defects in rice development. Therefore, future studies should consider the potential application of *OsZF* in rice breeding using the CRISPR/Cas9 system.

The circadian clock and abiotic stress conditions impact gene expressions in plants (Sugiyama et al., 2001; Matsuoka et al., 2015). Thus, mock treatments were necessary in examining the expression of *Osa-miR159a* and its target genes during *M. oryzae* infection. The results showed that *Osa-miR159a* and its target genes were responsive to *M. oryzae* infection compared with the mock treatment at each time point (Fig. 1 and Fig. 4). However, the mock treatment strongly influences the expression of *Osa-miR159a* and its target genes, indicating that the expression of *Osa-miR159a* and its target genes may be strongly impacted by the circadian clock or/and abiotic stress conditions (i.e., mock treatment), but further studies are required. In addition, our results showed that knockout lines of *OsGAMYB* and *OsGAMYBL* exhibited increased resistance to *M. oryzae* (Fig. 5). It is important to determine how *Osa-miR159a* functions in rice immunity against *M. oryzae*. On one hand, this is consistent with previous results that have shown that MYB transcription factors are involved in rice immunity. For example, the repressive MYB transcription factor, *MYBS1*, results in reduced expression of *broad-spectrum resistance-Digui 1 (bsr-d1)* allele from the rice cultivar Digu, thus, inhibiting *H$_2$O$_2$* degradation and enhanced disease resistance (Li et al., 2017). *MYB30* bonds to and activates the promoter of the 4-coumarate:coenzyme A ligase genes Os4CL3 and Os4CL5, resulting in accumulation of lignin subunits G and S, further leading to obvious thickening of sclerenchyma cells and inhibiting *M. oryzae* penetration (Li et al., 2020). BGISOSG004670, the homolog of *GAMYB* in *Arabidopsis*, showed increased expression upon fungal infection, suggesting that *GAMYB*-like genes might be involved in resistance to fungal infection (Li et al., 2016). The novel MYB
transcription factor CaPHL8 acts as a positive regulator in the resistance of pepper to *Ralstonia solanacearum* (Noman et al., 2019). On the other hand, *GAMYB* is involved in GA-signaling; thus, *GAMYB* may regulate rice immunity by manipulating plant hormones. Moreover, loss-of-function of *ZF* also results in enhanced resistance to *M. oryzae*. Zinc finger proteins are involved in plant growth and development. Overexpression of *zinc finger protein 1* (*GhZFP1*) enhances resistance to *Rhizoctonia solani* (Guo et al., 2009). In the future, we will focus on the function of *ZF* in the resistance of rice immunity to *M. oryzae*.

An increasing number of studies have shown that the production of RNAi-inducing dsRNA in the host can result in specific fungal gene silencing, further conferring resistance to fungal pathogens (Zhang, T et al., 2016). In response to *Verticillium dahlia* infection, cotton plants increase mir166 and mir159 expression, and export them to fungal hyphae for silencing key genes that are essential for fungal virulence (Zhang, T et al., 2016). Hence, we cannot exclude the possibility that *Osa-miR159a* may also be exported to the fungal hyphae of *M. oryzae* to silence genes that are essential for fungal virulence. Future studies are required to confirm this hypothesis.

**Conclusions**

We functionally characterized *Osa-miR159a* and its target genes in rice resistance to *M. oryzae*. Our data indicated that *Osa-miR159a* positively regulated resistance to *M. oryzae* and impacted yield traits by regulating its target genes *OsGAMYB*, *OsGAMYBL*, and *OsZF*. Suppressed expression of *OsGAMYB*, *OsGAMYBL*, and *OsZF* by overexpressing *Osa-miR159a* or knockout of *OsGAMYB*, *OsGAMYBL*, and *OsZF* resulted in enhanced resistance to *M. oryzae*, but led to developmental defects. In contrast, blocking *Osa-miR159a* via STTM led to significantly increased susceptibility and defects in yield traits. Therefore, proper spatiotemporal expression of *Osa-miR159a* was critical for rice immunity and development. *Osa-miR159a* and the regulatory module of its target genes could be used to breed rice with resistance to *M. oryzae*.

**Materials And Methods**

**Plant Materials and Growth Conditions**

*Oryza sativa* *Japonica* accessions Nipponbare (NPB) and Zhong Hua 11 (ZH11) were used for transgenic analysis. The susceptible accession Lijiangxin Tuan Heig (LTH) and the resistant accession International Rice Blast Line Pyricularia-Kanto51-m-Tsuyuake (IRBLkm-Ts) was used in this study. The rice plants were grown in a growth chamber maintained at 26°C and 70% relative humidity under 12 hours of light and 12 hours of darkness. To assay yield traits, rice plants were grown in a paddy field in the Wenjiang district of Chengdu, China, from April to September.

**Analysis of Yield Traits**

Rice agronomic traits were measured from five plants in the paddy field at maturity. The 1,000 grain weight, grain length, and grain width were measured using an SCA grain analysis system (Wanshen Ltd., Hangzhou, China) using the filled grains that were dried in an oven at 42 °C for 1 week. These data were analyzed by a one-way ANOVA followed by post hoc Tukey’s HSD analysis. Differences were considered significant at P < 0.01.

**Plasmid Construction and Genetic Transformation**

To construct the transgenic line overexpressing *Osa-miR159a*, we amplified the DNA sequence containing 321 bp upstream and 306 bp downstream of *Osa-miR159a* from NPB genomic DNA with the specific primers miR159a-KpnF and miR159a-Sal-R (Table S1), then the amplified DNA fragments were digested and cloned into the binary vector 3SS-pCAMBIA1300 at KpnI and SalI sites, resulting in the overexpressing construct. To construct the transgenic lines overexpressing the short tandem target mimic (STTM) of *Osa-miR159a* (STTM159), we inserted the amplified DNA fragments of STTM159 into the KpnI and SalI sites of the binary vector 3SS-pCAMBIA1300, resulting in a target mimic of the miR159 construct. The entire sequences of STTM159 were 5′-ggattctgcagctctgtgatccgaggcatggaattgttgtttattctgctcaaaatatttcgctcaaacac3′. Both of the constructs were transformed into the NPB background via Agrobacterium-mediated transformation. To generate *Osa-miR159a* target gene knockout lines, we constructed the CRISPR/Cas9 plasmids as described previously (Zhao et al., 2019). The constructs were transformed into the ZH11 background via *Agrobacterium* strain GV3101. All the positive transgenic lines were confirmed using hygromycin. To confirm the genotype of the knockout lines, we performed PCR-based gene sequencing as described previously (Zhao et al., 2019). All primers are listed in Table S1.

**Pathogen Infection and Microscopy Analysis**

*Magnaporthe oryzae* strains Guy11 and eGFP-tagged Zhong10-8-14 (GZ8) was used in this study. The strain was incubated on oatmeal and tomato agar media (OTA) at 28°C under a 12-hour light and 12-hour dark cycle. After 10 days, the hyphae were scratched, and the fungus on the plates was further incubated with 24-hour light treatment to promote sporulation. Three to 5 days later, the spores were collected for spray- or punch-inoculation. For spray-inoculation, seedlings at the three-leaf-stage were inoculated with a spore suspension (3×10^6 conidia/mL). Disease lesions were recorded at five days post-inoculation (dpi). For punch-inoculation, 5 μL of the spore suspension (5×10^5 spore/mL) was drop-inoculated at wound sites on the leaves of seedlings at the three-leaf-stage following previously described methods (Li et al., 2014). Briefly, the dilution-drop conidia suspension was placed against wounded sites on the leaves. Lesion formation was examined at 4–6 dpi. The relative fungal mass was calculated using the DNA concentration of *M. oryzae* *Pot2* against the rice genomic *UBiquitin* DNA level by quantitative PCR.

*M. oryzae* strain GZ8 was used to observe the fungal infection process. Leaf sheaths (5-cm-long) were inoculated with a spore suspension (1×10^4 conidia/mL) as described previously (Li et al., 2014). The inoculated epidermal layer was excised for observation. We observed the invasion process including appressorium development and invasive hyphal growth with a Laser Scanning Confocal Microscope (Nikon A1) at 24-, 36-, and 48-hour. The quantitative analysis of the infestation stage was conducted as described previously (Li, Y et al., 2017).
Reverse Transcription Quantitative Polymerase Chain Reaction (RT-qPCR)

The leaves of OX159 and STTM159 were collected to detect the amounts of miRNA and target genes. To examine the expressions of defense-related genes, we inoculated seedlings in the three-leaf-stage with *M. oryzae* using the spray inoculation method. The inoculated leaf samples were collected at 0, 6, 12, and 24 hpi. Total RNA was extracted, then reverse transcription was performed following a previous report (Zhao et al., 2020). To analyze the expression of miRNA, we performed a stem-loop pulse RT-qPCR following a previous report (Turner et al., 2013). U6 snRNA was used as an internal reference to normalize data.

Abbreviations

STTM: short tandem target mimic; ARF: auxin response factor; LTH: Lijiangxin Tuan Heigu; IRBLkm-Ts: International Rice Blast Line Pyricularia-Kanto51-m-Tsuyuake; NB: Nipponbare; ZH11: Zhong Hua 11; CRISPR: clustered regularly interspaced short palindromic repeats; OTA: tomato agar media; RT-qPCR: reverse transcription quantitative polymerase chain reaction; LSCM: laser scanning confocal microscopy; TCP: PROLIFERATING CELL NUCLEAR ANTIGEN BINDING FACTOR.

Declarations

Acknowledgments

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Authors’ Contributions

J.-F.C. performed the experiments with support from Z.-X.Z., Y.L., T.-T.L., Y.Z., X.-M.Y., S.-X.Z., H.W., J.-Q.Z., M.P., H.F., J.F., J.-W.Z., and Y.-Y.H. W.-M.W. conceived the project and designed the experiments. Z.-X.Z., J.-F.C., and W.-M.W. analyzed the data; Z.-X.Z., Y.L. and W.-M.W. wrote the manuscript. J.-F.C. Z.-X.Z. and Y.L. contributed equally to this work.

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Availability of Data and Materials

All of the datasets are included within the article and its additional files.

Ethics Approval and Consent to Participate

Not applicable.

Consent for Publication

Not applicable.

Competing Interests

All the authors declare no conflict of interests.

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Supplementary Figure Legends

Supporting Information

Figure S1. Overexpression of Osa-miR159a results in enhanced resistance to Magnaporthe oryzae. a Blast disease phenotype at 5 days post-inoculation (dpi) with M. oryzae strain GZ8. Scale bars, 10 mm. b Relative lesion area on the inoculated leaves from (a). Error bars indicate standard deviation (SD) (n=3). Asterisks (*) above the bar indicates significant differences (P<0.01) determined by the Student's t-test. c Confocal images showing the infection status of...
eGFP-tagged *M. oryzae* strain GZ8 in the indicated lines at 24, 36, and 48 hours post-inoculation (hpi). Scale bars, 25 μm. d Quantification analysis on the process of GZ8 infection in the indicated lines at the indicated time points. Over 200 conidia in each line were analyzed. The experiments were repeated two times with similar results. e The expression of defense-related genes in wild type and OX159 lines following the inoculation of *M. oryzae* strain GZ8. RNA was extracted at the indicated time points for the reverse transcription-quantitative PCR (RT-qPCR) assay. The amounts of collected mRNA were normalized to that in the wild type at 0 hpi. Error bars indicate SD (n=3). Different letters above the bars indicate significant differences (P<0.01) as determined by a one-way ANOVA followed by post hoc Tukey’s HSD analysis.

Figure S2. Overexpression of STTM159 results in enhanced susceptibility to *Magnaporthe oryzae*. a Blast disease phenotype at 5 days post-inoculation (dpi) with *M. oryzae* strain GZ8. Scale bars, 10 mm. b, c Relative fungal growth and lesion area on the inoculated leaves from (a). Error bars indicate SD (n=3). Asterisks (*) above the bar indicates significant differences (P<0.01) determined by the Student’s t test. d Confocal images showing the infection status of a GFP-tagged *M. oryzae* strain GZ8 in the indicated lines at 24, 36, and 48 hours post-inoculation (hpi). Scale bars, 25 μm. e Quantification analysis of the process of GZ8 infection in the indicated lines at the indicated time points. Over 200 conidia in each line were analyzed. The experiments were repeated two times with similar results. f–h The expression of defense-related genes in wild type (WT) and STTM159 lines following the inoculation of *M. oryzae* strain GZ8. RNA was extracted at the indicated time points for the reverse transcription-quantitative PCR (RT-qPCR) assay. The amounts of collected mRNA were normalized to that in the WT at 0 hpi. Error bars indicate SD (n=3). Different letters above the bars indicate significant differences (P<0.01) as determined by a one-way ANOVA followed by post hoc Tukey’s HSD analysis.

Figure S3. *Osa-miR159* mature isoforms and the accumulation of *Osa-miR159a* target genes in the indicated lines. a The sequence alignments of *Osa-miR159* mature isoforms and their positions on the chromosome in rice. b The structure of target genes and the sequence alignment of the target sites in the target genes. White boxes indicate the 5'-UTRs and 3'-UTRs. Black boxes indicate exons. Black lines indicate introns. Red lines indicate the target sites of *Osa-miR159a*. c Reverse transcription-quantitative PCR (RT-qPCR) data show the relative mRNA amount of target genes in OX159 and STTM159 in comparison with NPB containing the empty vector (EV). Data are shown as mean ± SD (n = 3). Different letters above bars indicate significant differences (P<0.05) as determined by a one-way ANOVA followed by post hoc Tukey’s HSD analysis.

Figure S4. The phenotype and 1,000-grain weight (g) of the *zf* mutants. a The phenotype of *zf* mutants and EV control at the reproductive stage. The height of *zf* mutants slightly less than that of the wild type plants. b The 1,000-grain weight (g) of the indicated plants showed no difference.

Table S1. The primers used in this research

Figures

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**Figure 1**

*Osa-miR159a* is differentially responsive to *Magnaporthe oryzae* in the susceptible and resistant accessions. a Representative leaves show the blast disease phenotype at five days post-inoculation (dpi) with *M. oryzae* strain GZ8 in LTH and IRBLKm-Ts. Scale bars, 10 mm. b Reverse transcription-quantitative PCR (RT-qPCR) shows the accumulation of *Osa-miR159a* in LTH and IRBLKm-Ts upon *M. oryzae* or mock treatment at the indicated time points. Error bars indicate SD (n=3). Different letters above bars indicate significant differences (P<0.05) as determined by a one-way ANOVA followed by Tukey’s HSD post hoc test. This experiment was repeated two times with similar results.
Figure 3

Osa-miR159a influences rice traits and yield. a, b Gross morphology of the indicated lines. Scale bars, 20 cm. c, d Panicles morphology of the indicated lines. Scale bars, 2 cm in (d). e, f Shucked grains of the indicated lines. Scale bars, 2 mm. g Potassium iodide dye shows the starch in the pollen grain of the indicated lines. Scale bars, 100 μm. h-k Potassium iodide dye shows the starch in seeds of the indicated lines. The pictures in (h, k) were captured before potassium iodide dye. The pictures in (i, j) were captured after potassium iodide dye. l, m Comparison of grain width (l) and grain length (m) in the indicated lines. Scale bars, 5 mm.
Figure 5

The mutations of Osa-miR159a target genes result in enhanced resistance against Magnaporthe oryzae. a-c The genotype of Osa-miR159a target gene knockout lines were confirmed by PCR based sequencing. Ref means reference sequences. d Blast disease phenotype at five days post-inoculation (dpi) with M. oryzae strain GZ8 in the indicated lines. Scale bars, 10 mm. e,f Relative fungal biomass (e) and lesion length (f) on the inoculated leaves from (d). Data are shown as mean ± SD (n = 3). Different letters above bars indicate significant differences (P<0.05) as determined by a one-way ANOVA and Tukey’s HSD post hoc test. The experiments were repeated two times with similar results.

Supplementary Files

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- FigS4.png