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RESEARCH ARTICLE

# Isolating higher yielding and more stable rice genotypes in stress environments: fine-tuning a selection method using production and resilience score indices

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**KEYWORDS**

Aerobic rice, breeding selection, drought resilience, production capacity index, resilience capacity index, stress score index, upland

## HIGHLIGHTS

- Score index methods readily discriminate genotypes adapted to a target environment.
- New quantitative method evaluated productivity and resilience of rice genotypes.
- Method identified A genotypes (high productivity and resilience) of Fernandez (1992).
- Method identified genotypes better adapted to reduced soil water conditions.
- Method can enhance rice sustainability (high productivity, low water use).

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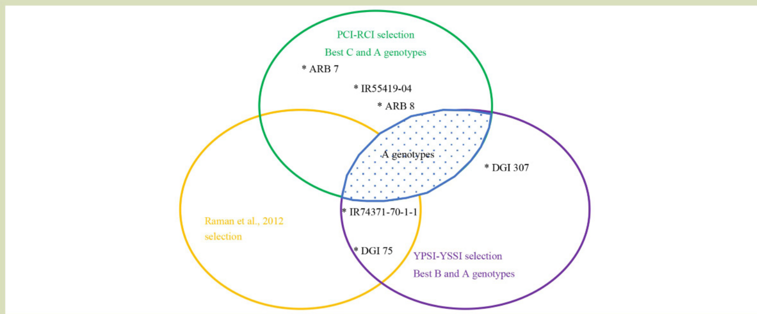
## GRAPHICAL ABSTRACT




## ABSTRACT

In Asia, the rice crop sustains millions of people. However, growing demand for this crop needs to be met while simultaneously reducing its water consumption to cope with the effects of climate change. Lowland cropping systems are the most common and productive but have particularly high water requirements. High-yielding rice genotypes adapted to drier environments (such as rainfed or aerobic rice ecosystems) are needed to increase the water use efficiency of cropping. Identifying these genotypes requires fast and more accurate selection methods. It is hypothesized that applying a new quantitative selection method (the score index selection method), can usefully compare rice yield responses over different years and stress intensities to select genotypes more rapidly and efficiently. Applying the score index to previously published rice yield data for 39 genotypes grown in no-stress and two stress environments, identified three genotypes (ARB 8, IR55419-04 and ARB 7) with higher and stable yield under moderate to severe stress conditions. These genotypes are postulated to be better adapted to stress environment such as upland and aerobic environments. Importantly, the score index selection method offers improved precision than the conventional breeding selection method in identifying genotypes that are well-suited to a range of stress levels within the target environment.

## 1 Introduction

Rice is one of the most important cereal crops globally, eaten by more than half the global population[1] and supplying 19% of daily per capita calorie consumption[2]. Asia produces more than 90% of world rice, with China (28%) and India (21%) producing about half[3,4]. As rice is a staple food for more than 60% of China, it is the largest producer and consumer of rice, producing 149 Mt and importing 4.6 Mt in 2021[5].

The Green Revolution, which doubled rice yield from the mid-1960s to the late 1980s, introduced new semidwarf rice genotypes (e.g., IR8, IR64 and IR72) combined with improved agronomic practices such as better use of agrochemicals and enhanced irrigation infrastructure[6]. Increasingly, climate change (especially drought stress) threatens the production and sustainability of food production including rice[7–9]. Addressing current and future demands for this crop poses a significant challenge, as it requires a substantial increase in productivity while optimizing the utilization of resources like land and water[8,10].

The most important rice ecotypes, lowland and upland, grow in distinct environments[11]. While lowland rice is usually grown in flooded fields during part or all of the growing season, upland rice is more adapted to drier conditions and generally grown on sloping or level fields[12]. More than 50% of global riceland is irrigated lowland, 25% is rainfed lowland (which can suffer some drought or flood stress) and the remainder upland (13%) and flood-prone (9%) ecosystems. Lowland rice ecotypes (irrigated and rainfed) are typical in Asia[13], with irrigated lowland representing more than 70% of global rice production[14].

Also, rice production consumes 35% to 45% of global water use in agriculture[15], with high-yielding irrigated lowland rice requiring about 4–5 kL to produce 1 kg of rice[10]. Adapting rice cultivation to reduce water consumption in irrigated lowlands demands identifying new cultivars combining drought resilience (upland rice) and high yield potential (irrigated lowland rice). This production system, called aerobic rice[10,16], produced less yield than the yield potential of irrigated lowland ecosystems, but some aerobic rice genotypes can yield up to 5 $t \cdot ha^{-1}$ with 60% less water than similar-yielding lowland rice[10,17]. Identifying these genotypes that yield well despite restricted water supply is necessary to enhance the economic and ecological sustainability of this crop.

Plant breeders are charged with ensuring high-yielding, stress resilient genotypes able sustain high yields in increasingly stressful environments, with many efforts being made to identify these drought-tolerant genotypes[18]. However, most crops have negative trade-offs between stress resilience and productivity. High-yielding rice genotypes are usually drought sensitive (most of the irrigated lowland rice genotypes), whereas upland rice is usually more drought resilient with poorer yield under optimal conditions with high water supply[11,12,19]. Currently, Chinese rice breeding programs apply a bidirectional selection strategy (selection between productivity and drought resistance, season by season), producing many recombinant genotypes by crossing upland and lowland rice, with high productivity and drought resilience[11].

To best identify how to measure genotypic variation in yield responses in contrasting environments (balance between productivity and stress resilience), crop breeders have used different methods[20]. Stress indices developed initially to screen genotypes for drought stress tolerance in wheat[21] have been applied in many crops including rice. The most commonly used are the stress susceptibility index (SSI), tolerance index (TOL), the mean productivity index (MP), the geometric mean productivity index (GMP) and the stress tolerance index (STI). These apply different equations using yield data obtained under yield potential (yield with no stress) and yield under stress. Genotypes are classified into four groups (A to D) based on their yield performance in no-stress and stress environments, but none of the suggested indices can clearly identify genotypes classified in Group A and fail to distinguish Group A from B or C. SSI and TOL tend to identify genotypes with more stable yield, while the other three indices better discriminate mean yield performance. These indices fail to properly evaluate the trade-off of yield performance and yield stability[22].

Combining indices might provide better criteria for selecting drought or heat stress-tolerant genotypes[23,24]. However, each index has its own scale, which hampers recombination. A new approach combined the five previously described stress indices (SSI, TOL, MP, GMP and STI) and implemented a scoring scale (from 1 to 10) to evaluate individual genotype yield response as a function of the mean response of the population or trial[22]. Scoring the stress indices allows them to be readily combined as they are expressed on the same scale (from 1 to 10). These scored indices were grouped into the production capacity index (PCI) and the resilience capacity index (RCI), with their combination developing a new index highly correlated with yield potential (yield potential score index, YPSI), and two others indices the yield stress score index

(YSSI) and the mean score index, which are highly correlated with yield under stress conditions[22]. The key innovation is fine-tuning the selection based on the PCI and the RCI analyzed individually[22].

To respond to global food demands and adapt the crop to lower soil water availability, rice breeders need to more rapidly and accurately identify potential cultivars with higher and stable yields in non-flooded contexts including rainfed lowland, upland and aerobic ecosystems[10,25]. This paper aims to demonstrate that applying the stress score index method, on published yield data of 39 elite rice lines evaluated under two different drought stress intensities[26], can quickly and more efficiently identify more productive rice genotypes in stress environments, with consistent responses over varying stress intensity (SI) and seasons. We assess if this method can be recommended to crop breeding programs to identify high-yielding rice genotypes, adapted to specific cropping environments such as irrigated lowland, rainfed lowland, upland and aerobic rice.

## 2 Materials and methods

In 2012, Raman et al.[26] reported a study in which yield of a subset of 39 elite genotypes from a panel of 129 advanced rice breeding lines was evaluated at three locations in India from 2005 to 2007 under stress (rainfed drought) and favorable irrigated conditions (no stress)[26]. To classify individual trial stress levels, the authors grouped them according to the yield reduction compared to the irrigated control, with moderate and severe drought stress decreasing yield by 31% to 65% and more than 65%, respectively. These 39 genotypes were selected to develop a drought yield index (DYI) (Table 1) with the mean yield index (MYI) compared to the yield deviation of two widely-grown cultivars (IR64 or MTU 1010). MYI is the mean value of the yield for each genotype in three environments (no, moderate and severe stress). To calculate how yield of each genotype deviated from a reference cultivar (namely, IR64 or MTU 1010), the authors calculated the difference between the yield of the reference cultivar and the yield of the genotype in each environmental context (no, moderate and severe stress). Each genotype received six values, one value for each reference cultivar (IR64 and MTU 1010) in each of the three environments. To compare the appropriateness of the different stress index calculations, the yield data provided by Raman et al.[26] was used to calculate the score indices PCI, RCI, YPSI and YSSI as previously described[22].

**Table 1 List of the different indices, formulae and references**

| Index name | Abbreviation | Formula |
|---|---|---|
| Stress susceptibility index | SSI[21] | $\mathrm{SSI} = \dfrac{1-\dfrac{\mathrm{Ys}}{\mathrm{Yp}}}{\mathrm{SI}}$ |
| Stress intensity | SI[21] | $\mathrm{SI} = \left[1-\dfrac{\overline{\mathrm{Ys}}}{\overline{\mathrm{Yp}}}\right]$ |
| Mean productivity | MP[27] | $\mathrm{MP} = \dfrac{\mathrm{Ys}+\mathrm{Yp}}{2}$ |
| Stress tolerance index | TOL[27] | $\mathrm{TOL} = \mathrm{Yp}-\mathrm{Ys}$ |
| Geometric mean productivity index | GMP[28] | $\mathrm{GMP} = \sqrt{\mathrm{Ys}\times\mathrm{Yp}}$ |
| Stress tolerance index | STI[28] | $\mathrm{STI} = \dfrac{\mathrm{Yp}\times\mathrm{Ys}}{\overline{\mathrm{Yp}}^2}$ |
| Drought yield index | DYI[26] | $\mathrm{DYI} = \dfrac{\dfrac{\mathrm{Yp}}{\mathrm{YS}}}{\dfrac{\overline{\mathrm{GYp}}}{\overline{\mathrm{GYs}}}}$ |
| Yield potential score index | YPSI[22] | $\mathrm{YPSI} = \left(\dfrac{(\mathrm{MPs}+\mathrm{STIs})}{2}-\dfrac{(\mathrm{SSIs}+\mathrm{TOLs})}{2}\right)$ |
| Yield stress score index | YSSI[22] | $\mathrm{YSSI} = \dfrac{\mathrm{SSIs}+\mathrm{STIs}}{2}$ |

Note: Ys, yield under stress conditions; Yp, yield potential (yield value under irrigated conditions); $\overline{\mathrm{Ys}}$, mean yields overall population under stress conditions; $\overline{\mathrm{Yp}}$, mean yields overall population under potential conditions; $\overline{\mathrm{GYs}}$, geometric mean yields overall population under stress conditions; and $\overline{\mathrm{GYp}}$, geometric mean yields overall population under potential conditions. In the formula for YPSI and YSSI, the lowercase "s" means the scored value of the original index. The productive component in the YPSI equation is the mean of MP-scored (MPs) and STI-scored (STIs) and the resilient component is the mean of SSI-scored (SSIs) and TOL-scored (TOLs). When the PCI component for YSSI is only STI-scored (STIs) and for the RCI component is only the SSI-scored (SSIs).

### 2.1 Calculating stress indices

Table 1 lists the arithmetic operations used to calculate the different indices as previously described[22]. To summarize, the score indices are calculated according to individual genotype yield responses, which are compared to the response of the whole population or panel using the maximum and minimum values to obtain the range value and to create the scale for each index. The range comprises 10 equal parts and each genotype obtains a score from 1 to 10, where 10 indicates the best response compared to the whole population and 1 denotes the worst.

### 2.2 Selection based on production and resilience capacity indices

In aiming to identify high-yielding and resilient genotypes in stress environments, genotypes with PCI and RCI values greater than the reference cultivars (IR64 and MTU 1010) were selected as previously recommended[22]. However, since the 39 genotypes were already a sub-selection of the best genotypes from a population of 129 advanced rice lines, most of the genotypes performed better than IR64 and MTU 1010. Thus, a second more restrictive selection criterion preselected genotypes with PCI and RCI superior or equal to 8.

### 2.3 Consistency of the score indices over years

Supplementary Section A evaluates another set of 36 genotypes with similar phenology (maturing in 100–120 days), including the six genotypes highlighted from previous analysis[26] and the same two reference cultivars (IR64 and MTU 1010), using supplied yield data[29]. These 36 genotypes were also evaluated in three environments (no, moderate and severe stress)[29] (Table S1).

### 2.4 Statistical analysis

We examined the correlation between the original indices and derived score indices[22]. Linear regression analysis was used to derive coefficients of determination ($R^2$) and Pearson correlation coefficient ($R$) using MS Excel (Microsoft Corporation, Redmond, WA, USA) and $R$ Core Team[30]. Additionally, we investigated correlations between the score indices and their combinations with measured yields under both no-stress and stress conditions.

## 3 Results

### 3.1 Score indices versus rice yield in different environments

First, the score indices were calculated for the 39 genotypes, from Raman et al.[26], in both moderate and severe stress environments. Most genotypes had scores greater than 5 in both environments (Table 2 and Table 3). The reference cultivar IR64 had PCI values in moderate (Table 2, PCI of 6) and severe stress environments (Table 3, PCI of 5), with a lower resilience than the mean RCI value in both environments (Table 2, RCI of 4; Table 3, RCI of 3). In contrast, MTU 1010 had higher PCI and RCI values than IR64, with 8 and 6 (Table 2) under moderate stress, and 7 and 5 under severe stress (Table 3), respectively. Compared to MTU 1010 (the best reference cultivar), 22 genotypes had similar or better performance under moderate stress in terms of PCI and RCI, and 23 genotypes had similar or better performance under severe stress. Across all genotypes, PCI and RCI were linearly related across the two stress environments (Pearson correlation coefficients $R$ = 0.78 and $R$ = 0.80, respectively). (Supplementary Section B, Fig. S1).

Under yield potential conditions, mean yield was 4.54 $t \cdot ha^{-1}$

**Table 2** List of the 39 advanced rice breeding lines showing the yield value under irrigated conditions (Yp) and moderate stress (Yms) (data from Raman et al.[26])

| Genotype ID | Yp ($t \cdot ha^{-1}$) | Yms ($t \cdot ha^{-1}$) | YPSI | YSSI | STIs (PCI) | MPs | GMPs | SSIs (RCI) | TOLs |
|---|---|---|---|---|---|---|---|---|---|
| Annada | 4.14 | 2.89 | −3.0 | 8 | 7 | 6 | 8 | 9 | 10 |
| ARB 2 | 4.33 | 2.98 | −1.5 | 8.5 | 8 | 8 | 9 | 9 | 10 |
| ARB 3 | 4.82 | 3 | 2 | 9 | 10 | 10 | 10 | 8 | 8 |
| ARB 4 | 4.27 | 2.73 | −2.0 | 7.5 | 7 | 6 | 7 | 8 | 9 |
| ARB 5 | 4.19 | 2.9 | −2.0 | 8.5 | 8 | 7 | 8 | 9 | 10 |
| ARB 6 | 4.64 | 2.7 | 1 | 7.5 | 8 | 8 | 8 | 7 | 7 |
| ARB 7 | 4.24 | 3 | −2.5 | 9 | 8 | 7 | 9 | 10 | 10 |
| ARB 8 | 4.47 | 3.35 | 0 | 10 | 10 | 10 | 10 | 10 | 10 |

(*Continued*)

| Genotype ID | Yp (t·ha$^{-1}$) | Yms (t·ha$^{-1}$) | YPSI | YSSI | STIs (PCI) | MPs | GMPs | SSIs (RCI) | TOLs |
|---|---|---|---|---|---|---|---|---|---|
| Baranideep | 4.61 | 2.87 | 0.5 | 8.5 | 9 | 8 | 9 | 8 | 8 |
| CB 0-15-24 | 4.38 | 2.89 | –1.5 | 8.5 | 8 | 7 | 8 | 9 | 9 |
| CB 2-458 | 4.65 | 2.4 | 0.5 | 6 | 6 | 7 | 7 | 6 | 6 |
| DGI 237 | 4.28 | 2.67 | –1.5 | 7.5 | 7 | 6 | 7 | 8 | 8 |
| DGI 307 | 4.91 | 2.88 | 3 | 8.5 | 10 | 10 | 10 | 7 | 7 |
| DGI 75 | 5.13 | 2.76 | 4.5 | 8 | 10 | 10 | 10 | 6 | 5 |
| DSL 104-1 | 4.9 | 2.95 | 2.5 | 9 | 10 | 10 | 10 | 8 | 7 |
| DSU 4-7 | 4.52 | 2.47 | –0.5 | 6 | 6 | 6 | 7 | 6 | 7 |
| IR36 | 3.89 | 1.78 | –4.0 | 3.5 | 2 | 1 | 2 | 5 | 6 |
| IR55419-04 | 4.39 | 2.96 | –1.0 | 8.5 | 8 | 8 | 9 | 9 | 9 |
| IR64 | 4.97 | 2.16 | 2.5 | 5 | 6 | 7 | 7 | 4 | 4 |
| IR66873-R-11-1 | 4.94 | 2.1 | 2.5 | 5 | 6 | 6 | 6 | 4 | 3 |
| IR67469-R-1-1 | 4.29 | 1.3 | –1.5 | 1.5 | 1 | 1 | 1 | 2 | 3 |
| IR72667-16-1-B-B-3 | 4.38 | 2.79 | –1.0 | 8 | 8 | 7 | 8 | 8 | 9 |
| IR74371-3-1-1 | 4.78 | 2.64 | 1.5 | 7.5 | 8 | 8 | 8 | 7 | 6 |
| IR74371-46-1-1 | 4.68 | 2.65 | 1 | 7.5 | 8 | 8 | 8 | 7 | 7 |
| IR74371-54-1-1 | 4.63 | 2.96 | 1 | 8.5 | 9 | 9 | 9 | 8 | 8 |
| IR74371-70-1-1 | 5.1 | 2.92 | 3.5 | 8.5 | 10 | 10 | 10 | 7 | 6 |
| IR74371-78-1-1 | 4.94 | 2.92 | 3 | 8.5 | 10 | 10 | 10 | 7 | 7 |
| Kallurundaikar | 4.51 | 2.65 | 0 | 7 | 7 | 7 | 8 | 7 | 7 |
| Khiradhan | 5.08 | 2.33 | 3 | 6 | 7 | 8 | 8 | 5 | 4 |
| MTU 1010 | 4.79 | 2.59 | 2 | 7 | 8 | 8 | 8 | 6 | 6 |
| NDR 1098-6 | 4.09 | 2.82 | –3.0 | 8 | 7 | 6 | 7 | 9 | 10 |
| PM 1011 | 4.58 | 2.89 | 0.5 | 8.5 | 9 | 8 | 9 | 8 | 8 |
| PMK 1 | 4.73 | 1.17 | 0.5 | 1 | 1 | 2 | 1 | 1 | 1 |
| PMK 2 | 4.22 | 1.36 | –1.5 | 1.5 | 1 | 1 | 1 | 2 | 3 |
| Poornima | 4 | 2.55 | –4.0 | 6.5 | 5 | 4 | 6 | 8 | 9 |
| R1027-2282-2-1 | 4.55 | 2.69 | 0.5 | 7.5 | 8 | 7 | 8 | 7 | 7 |
| RF 5329 | 4.32 | 2.85 | –1.5 | 8.5 | 8 | 7 | 8 | 9 | 9 |
| RR 272-21 | 4.33 | 2.66 | –1.5 | 7.5 | 7 | 6 | 7 | 8 | 8 |
| Tripuradhan | 4.55 | 2.88 | 0.5 | 8.5 | 9 | 8 | 9 | 8 | 8 |

Note: YPSI, yield potential score index; YSSI, yield score stress index; STIs, scored stress tolerance index; PCI, production capacity index; MPs, scored mean productive index; GMPs, scored geometric mean production index; SSIs, scored stress susceptibility index; RCI, resilient capacity index; TOLs, scored tolerance index. These indices were calculated from the yield data following the scoring method developed by Thiry et al.[22]. The color scale from red to green represents the lowest to highest values (YPSI scale is going from −4.5 (red) to 4.5 (green) and all the other indices are scaled from 1 (red) to 10 (green)).

**Table 3 List of the 39 advanced rice breeding lines showing the yield value under irrigated conditions (Yp) and severe stress (Yss) (data from Raman et al.[26])**

| Genotype ID | Yp (t·ha$^{-1}$) | Yss (t·ha$^{-1}$) | YPSI | YSSI | STIs (PCI) | MPs | GMPs | SSIs (RCI) | TOLs |
|---|---|---|---|---|---|---|---|---|---|
| Annada | 4.14 | 1.66 | –2 | 7.5 | 7 | 6 | 8 | 8 | 9 |
| ARB 2 | 4.33 | 1.71 | –0.5 | 8 | 8 | 7 | 8 | 8 | 8 |

(*Continued*)

| Genotype ID | Yp ($t\cdot ha^{-1}$) | Yss ($t\cdot ha^{-1}$) | YPSI | YSSI | STIs (PCI) | MPs | GMPs | SSIs (RCI) | TOLs |
|---|---|---|---|---|---|---|---|---|---|
| ARB 3 | 4.82 | 1.83 | 1.5 | 8.5 | 9 | 9 | 10 | 8 | 7 |
| ARB 4 | 4.27 | 1.86 | –1.5 | 8.5 | 8 | 7 | 9 | 9 | 9 |
| ARB 5 | 4.19 | 1.89 | –2 | 8.5 | 8 | 7 | 9 | 9 | 10 |
| ARB 6 | 4.64 | 1.73 | 1 | 7.5 | 8 | 8 | 9 | 7 | 7 |
| ARB 7 | 4.24 | 2.05 | –1.5 | 9.5 | 9 | 8 | 10 | 10 | 10 |
| ARB 8 | 4.47 | 2.19 | –0.5 | 10 | 10 | 9 | 10 | 10 | 10 |
| Baranideep | 4.61 | 1.66 | 1 | 7.5 | 8 | 8 | 8 | 7 | 7 |
| CB 0-15-24 | 4.38 | 2.01 | –1.5 | 9.5 | 9 | 8 | 10 | 10 | 10 |
| CB 2-458 | 4.65 | 1.4 | 1 | 5.5 | 6 | 7 | 7 | 5 | 6 |
| DGI 237 | 4.28 | 1.29 | –1 | 5 | 5 | 5 | 6 | 5 | 7 |
| DGI 307 | 4.91 | 1.84 | 3.5 | 8.5 | 10 | 10 | 10 | 7 | 6 |
| DGI 75 | 5.13 | 1.86 | 4 | 8.5 | 10 | 10 | 10 | 7 | 5 |
| DSL 104-1 | 4.9 | 1.48 | 2.5 | 6 | 7 | 8 | 8 | 5 | 5 |
| DSU 4-7 | 4.52 | 1.39 | 0 | 6 | 6 | 6 | 7 | 6 | 6 |
| IR36 | 3.89 | 0.45 | –2 | 1 | 1 | 1 | 1 | 1 | 5 |
| IR55419-04 | 4.39 | 2.15 | –0.5 | 10 | 10 | 9 | 10 | 10 | 10 |
| IR64 | 4.97 | 1.02 | 3.5 | 4 | 5 | 7 | 6 | 3 | 2 |
| IR66873-R-11-1 | 4.94 | 0.66 | 2.5 | 1.5 | 2 | 5 | 3 | 1 | 1 |
| IR67469-R-1-1 | 4.29 | 0.88 | –0.5 | 3 | 3 | 4 | 4 | 3 | 5 |
| IR72667-16-1-B-B-3 | 4.38 | 1.82 | –1 | 8.5 | 8 | 8 | 9 | 9 | 9 |
| IR74371-3-1-1 | 4.78 | 1.71 | 2 | 7.5 | 8 | 9 | 9 | 7 | 6 |
| IR74371-46-1-1 | 4.68 | 1.83 | 1.5 | 8.5 | 9 | 9 | 9 | 8 | 7 |
| IR74371-54-1-1 | 4.63 | 1.84 | 1 | 8.5 | 9 | 9 | 9 | 8 | 8 |
| IR74371-70-1-1 | 5.1 | 1.87 | 3.5 | 8.5 | 10 | 10 | 10 | 7 | 6 |
| IR74371-78-1-1 | 4.94 | 1.75 | 2.5 | 8 | 9 | 9 | 9 | 7 | 6 |
| Kallurundaikar | 4.51 | 1.96 | 0 | 9 | 9 | 9 | 10 | 9 | 9 |
| Khiradhan | 5.08 | 0.76 | 3.5 | 2 | 3 | 6 | 4 | 1 | 1 |
| MTU 1010 | 4.79 | 1.43 | 2.5 | 6 | 7 | 8 | 8 | 5 | 5 |
| NDR 1098-6 | 4.09 | 1.39 | –2 | 5.5 | 5 | 5 | 6 | 6 | 8 |
| PM 1011 | 4.58 | 1.25 | 0.5 | 5 | 5 | 6 | 6 | 5 | 5 |
| PMK 1 | 4.73 | 0.79 | 2 | 2.5 | 3 | 5 | 4 | 2 | 2 |
| PMK 2 | 4.22 | 0.77 | –1 | 2 | 2 | 3 | 3 | 2 | 5 |
| Poornima | 4 | 1.68 | –3 | 8 | 7 | 6 | 8 | 9 | 10 |
| R1027-2282-2-1 | 4.55 | 1.19 | 1 | 4.5 | 5 | 6 | 6 | 4 | 5 |
| RF 5329 | 4.32 | 1.86 | –1.5 | 8.5 | 8 | 7 | 9 | 9 | 9 |
| RR 272-21 | 4.33 | 1.26 | –0.5 | 5 | 5 | 5 | 6 | 5 | 6 |
| Tripuradhan | 4.55 | 2.03 | 0.5 | 9.5 | 10 | 9 | 10 | 9 | 9 |

Note: YPSI, yield potential score index; YSSI, yield score stress index; STIs, scored stress tolerance index; PCI, production capacity index; MPs, scored mean productive index; GMPs, scored geometric mean production index; SSIs, scored stress susceptibility index; RCI, resilient capacity index; TOLs, scored tolerance index. These indices were calculated from the yield data following the scoring method developed by Thiry et al.[22]. The color scale from red to green represents the lowest to highest values (YPSI scale is going from –4.5 (red) to 4.5 (green) and all the other indices are scaled from 1 (red) to 10 (green)).

with DGI 75 yielding the most (5.13 t·ha$^{-1}$) and IR36 the least (3.89 t·ha$^{-1}$) (Table 2 and Table 3). Under moderate stress with a mean yield of 2.62 t·ha$^{-1}$ and an SI of 0.42, ARB 8 yielded the most (3.35 t·ha$^{-1}$) and PMK 1 the least (1.17 t·ha$^{-1}$). Under severe stress with a mean yield of 1.54 t·ha$^{-1}$ and an SI of 0.66, ARB 8 also yielded the most (2.19 t·ha$^{-1}$) and IR36 the least (0.45 t·ha$^{-1}$). Thus, moderate stress conditions caused the greatest range of grain yields among the genotypes. ARB 8 produced more than 25% of the mean yield under moderate stress and more than 40% under severe stress.

The score indices allow easy visualization and classification of the genotype values of the original indices (SSI, TOL, MP, GMP and STI) and their correlation agreed with the original index values (Pearson correlation coefficient for SSI and TOL $R < -0.99$ and for MP, GMP and STI $R > 0.99$). An inverted scoring scale, from 1 to 10, explains the negative correlation between SSI and TOL, such that the lowest value of the original indices (SSI and TOL) indicate the best genotypes and was scored as a 10 and vice versa, as explained by Thiry et al.[22]. Given this correlation, the specific combination of indices was used to calculate YPSI and YSSI (Table 1).

Under both stress conditions (Fig. 1(a,b)), YPSI was highly correlated with yield under no-stress conditions (coefficient of determination $R^2 > 0.94$). In addition, under both stress conditions (Fig. 1(c,d), YSSI was highly correlated with yield under both stress conditions (coefficient of determination $R^2 > 0.99$). The high correlation between YPSI and YSSI with yield in no-stress and stress environments, respectively, Fig. 1 shows that expressing rice yield as a function of PCI and RCI is a valid approach, as in wheat[22].

Thiry et al.[22] recommended selecting genotypes for high productivity and high resilience based on PCI and RCI, as YSSI is the simplest equation related to yield under stress[22]. Therefore, PCI and RCI will help evaluate the susceptibility of rice genotypes to different stress environments. This technique simplifies the interpretation of the previous indices and facilitates selection using a quantitative criterion. For example, as stress increases from moderate to severe, small increases

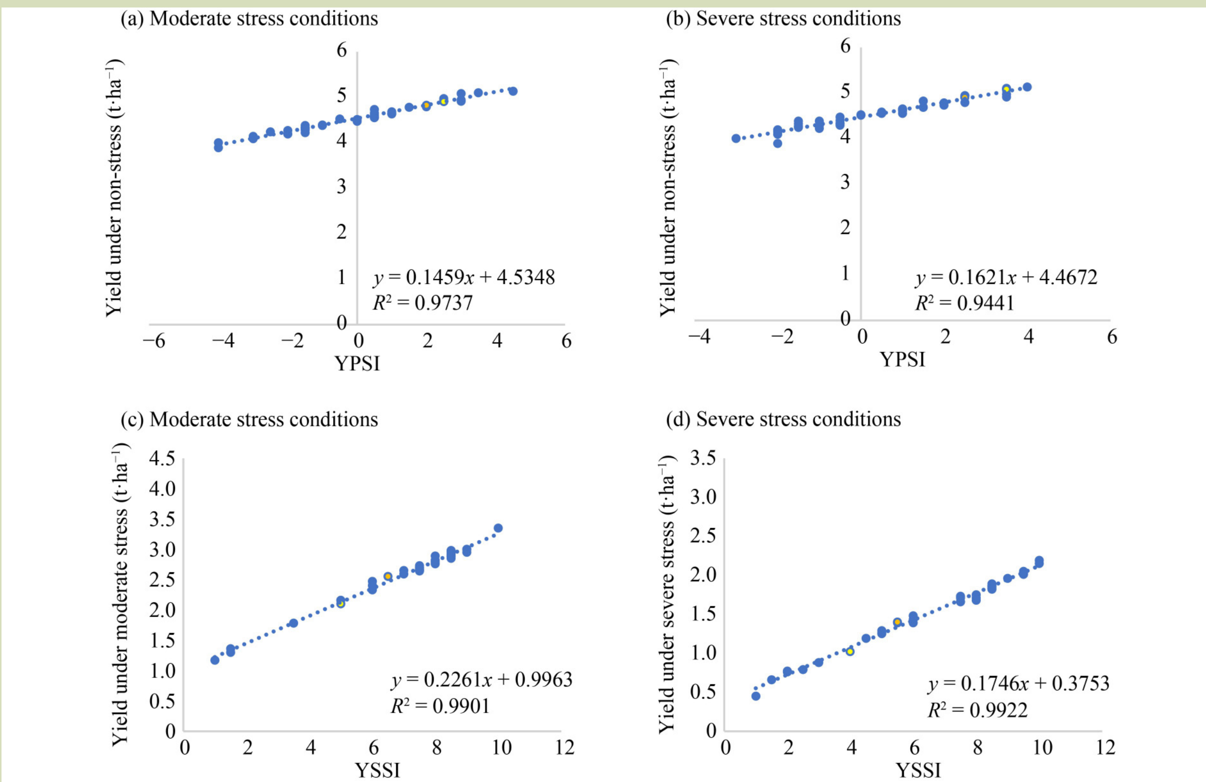



**Fig. 1** Linear regression and the coefficient of determination of the yield potential scored index (YPSI) versus yield under no stress (a and b) and yield stress scored index (YSSI) versus yield under moderate (c) and severe (d) stress conditions. Calculation of YPSI and YSSI use yield data from rice advanced line published in Raman et al.[26]. (a) and (c) are based on yield data from irrigated and moderate stress, when (b) and (d) on yield data from irrigated and severe stress environment. Each symbol is an individual genotype, yellow dot: IR64; orange dot: MTU 1010.

(1 or 2 units in the PCI and/or RCI values) by some genotypes indicate their yield decreased less than the overall population. Also, combining score indices (resulting in YPSI and YSSI) improved the interpretation of yield performance and the utility of the original indices.

### 3.2 Selecting high-yielding genotypes with suitable stress tolerance

Table 4 summarizes all genotypes with better score values of YPSI and YSSI than the reference cultivars (IR64 and MTU 1010) under both stress environments. Five genotypes stood out under both stress intensities: DGI 307, DGI 75, DSL 104-1, IR74371-70-1-1 and IR74371-78-1-1. Under moderate stress, all genotypes had a PCI value of 10 and RCI values ranging from 6 (DGI 75) to 8 (DSL 104-1). Under severe stress, PCI and RCI of DSL 104-1 were substantially less than under moderate stress, indicating a lower resilience under severe stress than the other four selected genotypes. These four genotypes (DGI 307, DGI 75, IR74371-70-1-1 and IR74371-78-1-1) averaged 2.87 t·ha$^{-1}$ under moderate stress and 1.83 t·ha$^{-1}$ under severe stress, 11% and 28% higher, respectively, than the best reference cultivar, MTU 1010 (Table 4). However, ARB 8 yielded more (3.35 and 2.19 t·ha$^{-1}$ under moderate and severe stress, respectively; Table 2 and Table 3). Therefore, this method distinguishes the best yielding genotypes in the no-stress environment with better yield under stress than the reference cultivars (IR64 and MTU 1010). However, under stress conditions these genotypes are not the best yielding genotypes within this population, as ARB 8 yielded better.

This method is similar to the standard method based on yield performance in both environments but fine-tuning of PCI and RCI discarded DSL 104-1 and IR74371-78-1-1, with the latter not retained as its PCI decreased between moderate and severe stress. Over both stress intensities, this selection method identified IR74371-70-1-1, DGI 75 and DGI 307 as the top 3, but Raman et al.[26] discarded DGI 307 in 2012.

### 3.3 Selecting high-yielding and stress-tolerant genotypes

Table 5 shows genotypes with PCI and RCI values ⩾ 8 under moderate stress and severe stress. The score indices (PCI and

**Table 4 List of selected rice genotypes using YPSI and YSSI**

| Genotype ID | Moderate stress | | | | | |
|---|---|---|---|---|---|---|
| | Yp (t·ha$^{-1}$) | Yms (t·ha$^{-1}$) | YPSI | YSSI | PCI | RCI |
| DGI 307 | 4.91 | 2.88 | 3 | 8.5 | 10 | 7 |
| DGI 75 | 5.13 | 2.76 | 4.5 | 8 | 10 | 6 |
| DSL 104-1 | 4.9 | 2.95 | 2.5 | 9 | 10 | 8 |
| IR74371-70-1-1 | 5.1 | 2.92 | 3.5 | 8.5 | 10 | 7 |
| IR74371-78-1-1 | 4.94 | 2.92 | 3 | 8.5 | 10 | 7 |
| MTU 1010 | 4.79 | 2.59 | 2 | 7 | 8 | 6 |
| IR64 | 4.97 | 2.16 | 2.5 | 5 | 6 | 4 |
| **Genotype ID** | **Severe stress** | | | | | |
| | Yp (t·ha$^{-1}$) | Yss (t·ha$^{-1}$) | YPSI | YSSI | PCI | RCI |
| DGI 307 | 4.91 | 1.84 | 3.5 | 8.5 | 10 | 7 |
| DGI 75 | 5.13 | 1.86 | 4 | 8.5 | 10 | 7 |
| DSL 104-1 | 4.9 | 1.48 | 2.5 | 6 | 7 | 5 |
| IR74371-70-1-1 | 5.1 | 1.87 | 3.5 | 8.5 | 10 | 7 |
| IR74371-78-1-1 | 4.94 | 1.75 | 2.5 | 8 | 9 | 7 |
| MTU 1010 | 4.79 | 1.43 | 2.5 | 6 | 7 | 5 |
| IR64 | 4.97 | 1.02 | 0 | 9.5 | 5 | 3 |

Note: Yp, yield value under irrigated conditions; Yms, yield under moderate stress; Yss, yield under severe stress; YPSI, yield potential score index; YSSI, yield stress score index; PCI, production capacity index; RCI, resilient capacity index. Genotypes ID highlighted in purple show the common genotypes between stress intensity, while those highlighted in light blue show the reference genotypes. The color scale from red to green represents the lowest to highest values (YPSI scale is going from –4.5 (red) to 4.5 (green) and all the other indices are scaled from 1 (red) to 10 (green)).

RCI) group genotypes with similar response within a 10% range. Among the 39 genotypes, 14 were selected, with 11 common between stress intensities (ARB 2, ARB 3, ARB 5, ARB 7, ARB 8, CB 0-15-24, IR55419-04, IR72667-16-1-B-B-3, IR74371-54-1-1, RF 5329 and Tripuradhan). These 11 genotypes consistently performed well across stress levels. Notably, reference cultivars had lower PCI and RCI values than the entire population. Under moderate stress (Table 5), ARB 8 had the highest PCI and RCI values of 10. ARB 3 and DSL 104-1 had the highest PCI values and ARB 7 had the highest RCI value (10). Under severe stress (Table 5), within the 11 common genotypes, ARB 8, IR55419-04 and Tripuradhan had the best values for PCI (10, 10 and 10) and RCI (10, 10 and 9). Also, ARB 7 and CB 0-15-24 had a high PCI value (9) and the highest RCI value (10). Genotypes ARB 7, CB 0-15-24, IR55419-04 had higher PCI values under severe stress than under moderate stress. Using PCI and RCI more easily discriminates genotypes than the original indices. The top three genotypes (ARB 8, IR55419-04 and ARB 7) had stable yield responses over both stress intensities, with CB 0-15-24 in fourth position.

Both selection methods using score indices are easy and simple to use but as they identify two different sets of genotypes, it needs to be decided which method should be used. The choice of selection method depends on breeding objectives: isolating the highest-yielding genotypes under no stress with acceptable yield resilience under stress or identifying the highest stable yield genotypes with high productivity in stress environment. Examining the yield vs stress intensity relationship clarifies these conclusions.

## 3.4 Yield versus stress intensity

Yield was plotted against SI for the six best genotypes from both selection methods (ARB 8, IR55419-04, ARB 7, IR74371-70-1-1, DGI 75 and DGI 307) and the reference cultivars (Fig. 2). Control conditions were assumed to be stress-free, thus SI = 0 (Fig. 2). At an SI of 0.16, ARB 8 outperformed the reference cultivars (IR64 and MTU 1010) and consistently surpassed IR55419-04 and ARB 7. Similarly, when SI reached 0.23 and 0.28, IR55419-04 and ARB 7 respectively outyielded the reference cultivars. Notably, IR74371-70-1-1 and DGI 75 consistently outperformed the reference cultivars, while DGI 307 surpassed them with limited, likely not significant, additional stress (SI = 0.04, following this simple model).

The simplified model (Fig. 2) effectively demonstrates the trade-off between yield performance and stress intensities for these genotypes compared to the reference cultivars. ARB 8 outperformed all other genotypes when SI exceeded 0.32, while IR55419-04 and ARB 7 outperformed IR74371-70-1-1, DGI 75 and DGI 307 when SI exceeded 0.42 and 0.46, respectively, indicating moderate stress intensity. Therefore, under moderate stress, ARB 8 emerges as the most productive genotype followed by IR55419-04 and ARB 7. Ultimately, all these six selected genotypes perform better than the reference cultivars, with the choice depending on the stress intensity of the target environments (irrigated lowland, rainfed lowland, aerobic and upland).

## 3.5 Genotype classification: Fernandez versus Thiry

Although A genotypes were considered the most adapted across a range of environments (Fig. 3(a))[22,28], the original stress indices (SSI, TOL, MP, GMP and STI) were insufficient to differentiate A genotypes from B or C genotypes. Thiry et al.[22] proposed using PCI and RCI to categorize these genotypes as shown in Fig. 3(b). This comparison shows that group B has a larger and more complex distribution in terms of PCI and RCI values than groups A and C which have a smaller area (Fig. 3(b)). The best B and C genotypes are the closest to the rare A genotype area (Fig. 3(b)). This theoretical distribution demonstrates that PCI and RCI values better classify the genotypes into these categories compared to using only yield values.

Rationalizing the two different sets of selected genotypes reveal the limitations of examining genotype distributions to identify more precisely A genotypes based on PCI and RCI. In fact, identifying A genotypes within a population requires at least one representative within the evaluated panel. This issue also exists with standard yield performance selection, explaining why most genotypes selected over decades are good B genotypes and rarely A genotypes. Supplementary Section C (including Fig. S2) illustrates and explains that limitation, showing the distribution of the genotypes as a function of PCI and RCI indices and confirming the method allows breeders to distinguish and better classify the genotypes as previously suggested[22].

Therefore, selection methods must be chosen and interpreted carefully, considering the target environments for breeders or farmers. Consequently, when panels have no A genotypes, the YPSI-YSSI method is recommended for no stress to moderate target environments, highlighting high-yielding genotypes with suitable stress resilience. However, this method may not perform as well when stress intensity increases (as it is favoring the best B genotypes). In contrast, for target environments with

**Table 5 List of the genotypes with a response superior to 80% of the population in moderate and severe stress environments in terms of production capacity index (PCI) and resilience capacity index (RCI)**

| Genotype ID | Moderate stress | | | |
|---|---|---|---|---|
| | Yp (t·ha$^{-1}$) | Yms (t·ha$^{-1}$) | PCI | RCI |
| ARB 2 | 4.33 | 2.98 | 8 | 9 |
| ARB 3 | 4.82 | 3.00 | 10 | 8 |
| ARB 5 | 4.19 | 2.90 | 8 | 9 |
| ARB 7 | 4.24 | 3.00 | 8 | 10 |
| ARB 8 | 4.47 | 3.35 | 10 | 10 |
| Baranideep | 4.61 | 2.87 | 9 | 8 |
| CB 0-15-24 | 4.38 | 2.89 | 8 | 9 |
| DSL 104-1 | 4.9 | 2.95 | 10 | 8 |
| IR55419-04 | 4.39 | 2.96 | 8 | 9 |
| IR72667-16-1-B-B-3 | 4.38 | 2.79 | 8 | 8 |
| IR74371-54-1-1 | 4.63 | 2.96 | 9 | 8 |
| PM 1011 | 4.58 | 2.89 | 9 | 8 |
| RF 5329 | 4.32 | 2.85 | 8 | 9 |
| Tripuradhan | 4.55 | 2.88 | 9 | 8 |
| IR64 | 4.97 | 2.16 | 6 | 4 |
| MTU 1010 | 4.79 | 2.59 | 8 | 6 |

| Genotype ID | Severe stress | | | |
|---|---|---|---|---|
| | Yp (t·ha$^{-1}$) | Yss (t·ha$^{-1}$) | PCI | RCI |
| ARB 2 | 4.33 | 1.71 | 8 | 8 |
| ARB 3 | 4.82 | 1.83 | 9 | 8 |
| ARB 4 | 4.27 | 1.86 | 8 | 9 |
| ARB 5 | 4.19 | 1.89 | 8 | 9 |
| ARB 7 | 4.24 | 2.05 | 9 | 10 |
| ARB 8 | 4.47 | 2.19 | 10 | 10 |
| CB 0-15-24 | 4.38 | 2.01 | 9 | 10 |
| IR55419-04 | 4.39 | 2.15 | 10 | 10 |
| IR72667-16-1-B-B-3 | 4.38 | 1.82 | 8 | 9 |
| IR74371-46-1-1 | 4.68 | 1.83 | 9 | 8 |
| IR74371-54-1-1 | 4.63 | 1.84 | 9 | 8 |
| Kallurundaikar | 4.51 | 1.96 | 9 | 9 |
| RF 5329 | 4.32 | 1.86 | 8 | 9 |
| Tripuradhan | 4.55 | 2.03 | 10 | 9 |
| IR64 | 4.97 | 1.02 | 5 | 3 |
| MTU 1010 | 4.79 | 1.43 | 7 | 5 |

Note: Yp, yield value under irrigated conditions; Yms, yield under moderate stress; Yss, yield under severe stress. Genotypes ID highlighted in purple show the 11 common genotypes between stress intensity, while those highlighted in light blue show the reference genotypes. The color scale from red to green represents the lowest to highest values (color follow the scaled from 1 to 10).

moderate to severe stress, the PCI-RCI approach is recommended, highlighting the most adapted and highest-yielding genotypes under these conditions (the best C genotypes). Common genotypes between the YPSI-YSSI and

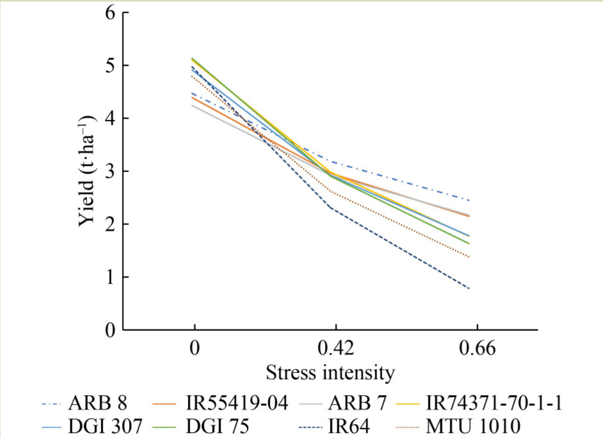



**Fig. 2** Yield linear model of the reference cultivars (IR65, MTU 1010) and the six highlighted genotypes (IR74371-70-1-1, DGI 75, DGI 307, ARB 8, IR55419-04 and ARB 7) versus stress intensity.

PCI-RCI methods identify the presence of A genotypes in the panel. If they are present within a panel, this is probably the best way to truly recognize A genotypes.

## 3.6 Raman selection versus score index methods

In Raman et al.'s[26] analysis, DYI better identified genotypes with high yield under stress conditions (moderate and severe stress) than SSI or TOL. Among the highlighted drought-tolerant genotypes (Annada, ARB 5, ARB 7, ARB 8, IR55419-04 and NDR 1098-6), ARB 8 and IR55419-04 were considered the best. However, it is unclear how ARB 8 and IR55419-04 were identified as the best using only DYI, as IR55419-04 had a lower rank under moderate stress and ARB 7 was favorably ranked under moderate stress intensities and similarly ranked under severe stress (Table 6; ARB 7 DYI 2 and 3 and IR55419-04 DYI 7 and 2, respectively). Reaching the same conclusion as Raman et al.[26] requires examining the MYI as these two genotypes (ARB 8 and IR55419-04) occur in the top seven (while ARB 7 was eleventh), showing the best DYI value under both stresses (Table 6), but this was not explained. Therefore, DYI alone seems insufficient to detect stress-tolerant genotypes.

In contrast, comparing these six genotypes (Annada, ARB 5, ARB 7, ARB 8, IR55419-04 and NDR 1098-6) with the score indices (PCI and RCI) revealed 4 common genotypes (ARB 5, ARB 7, ARB 8 and IR55419-04) with our method regarding three (ARB 8, IR55419-04 and ARB 7) as the best adapted genotypes to drought stress environments. Our PCI-RCI method discarded Annada and NDR 1098-6 under moderate and severe stress because their PCI were lower than 8 and under severe stress NDR 1098-6 had a RCI value lower than 8 (Table 1). Using PCI and RCI easily detected the most adapted genotypes to drought stress where ARB 8 was the best genotype under both stress intensities, with IR55419-04 performing similarly to ARB 7. Selection based on PCI and RCI more easily discriminates the best C genotypes. However, Raman et al.[26] discarded ARB 7 and only identified these two other genotypes as drought tolerant but do not recommend them as we do for target stress environments.

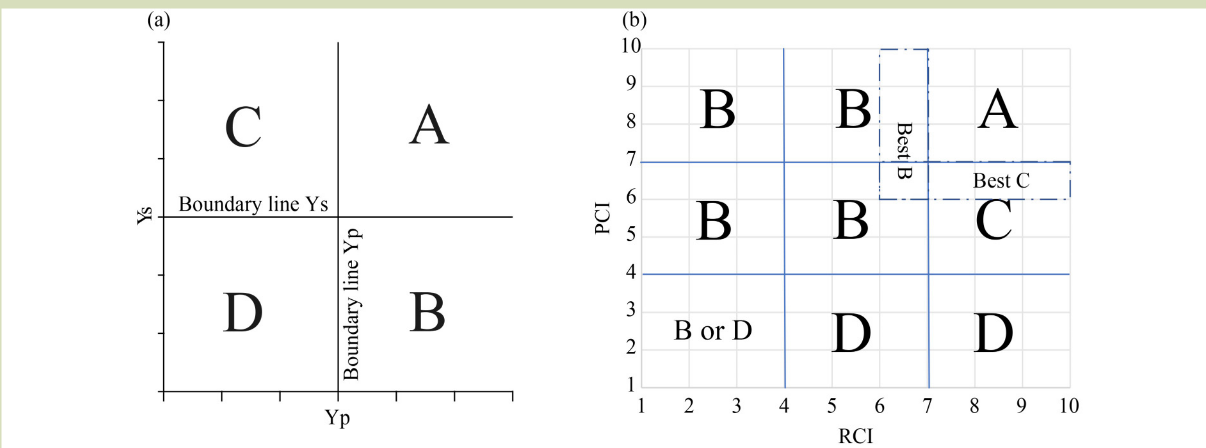



**Fig. 3** Diagram of genotype distribution into four genotype classes (A, B, C and D)[28] (a) as a function of yield under no stress (Yp) and stress (Ys) (b) as a function of the productivity capacity index (PCI) and the resilient capacity index (RCI). Modified from Thiry et al.[22] under Creative Commons.

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**Table 6 Summary of the indices used by Raman et al.[26] and their respective ranking value**

| Genotype ID | MYI | Ranking | Moderate stress | | Severe stress | | Deviation from IR64 mean | | | Deviation from MTU 1010 mean | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | DYI | Ranking | DYI | Ranking | Control | Moderate | Severe | Control | Moderate | Severe |
| Annada | 2.90 | 25 | 1.43 | 3 | 2.49 | 12 | −0.83 | 0.73 | 0.64 | −0.66 | 0.3 | 0.23 |
| ARB 2 | 3.01 | 19 | 1.45 | 5 | 2.53 | 14 | −0.64 | 0.83 | 0.69 | −0.47 | 0.4 | 0.28 |
| ARB 3 | 3.22 | 4 | 1.61 | 18 | 2.63 | 16 | −0.15 | 0.84 | 0.8 | 0.02 | 0.41 | 0.4 |
| ARB 4 | 2.95 | 22 | 1.57 | 11 | 2.3 | 7 | −0.7 | 0.57 | 0.83 | −0.52 | 0.14 | 0.43 |
| ARB 5 | 2.99 | 21 | 1.44 | 4 | 2.22 | 5 | −0.78 | 0.75 | 0.86 | −0.61 | 0.32 | 0.46 |
| ARB 6 | 3.02 | 17 | 1.72 | 25 | 2.69 | 18 | −0.33 | 0.55 | 0.7 | −0.16 | 0.12 | 0.3 |
| ARB 7 | 3.10 | 11 | 1.41 | 2 | 2.07 | 3 | −0.73 | 0.85 | 1.02 | −0.56 | 0.42 | 0.62 |
| ARB 8 | 3.34 | 1 | 1.33 | 1 | 2.05 | 1 | −0.49 | 1.2 | 1.16 | −0.32 | 0.77 | 0.76 |
| Baranideep | 3.05 | 14 | 1.6 | 16 | 2.78 | 21 | −0.36 | 0.72 | 0.64 | −0.18 | 0.29 | 0.23 |
| CB 0-15-24 | 3.09 | 12 | 1.51 | 8 | 2.18 | 4 | −0.59 | 0.74 | 0.99 | −0.42 | 0.31 | 0.58 |
| CB 2-458 | 2.82 | 26 | 1.94 | 32 | 3.32 | 27 | −0.31 | 0.24 | 0.38 | −0.14 | −0.19 | −0.03 |
| DGI 237 | 2.75 | 31 | 1.6 | 17 | 3.33 | 28 | −0.69 | 0.51 | 0.26 | −0.51 | 0.08 | −0.14 |
| DGI 307 | 3.21 | 5 | 1.71 | 24 | 2.67 | 17 | −0.06 | 0.72 | 0.81 | 0.12 | 0.29 | 0.41 |
| DGI 75 | 3.25 | 3 | 1.86 | 31 | 2.76 | 20 | 0.16 | 0.61 | 0.84 | 0.34 | 0.18 | 0.43 |
| DSL 104-1 | 3.11 | 10 | 1.66 | 20 | 3.31 | 26 | −0.07 | 0.79 | 0.46 | 0.1 | 0.36 | 0.05 |
| DSU 4-7 | 2.79 | 28 | 1.83 | 29 | 3.26 | 25 | −0.45 | 0.31 | 0.36 | −0.27 | −0.12 | −0.04 |
| IR36 | 2.04 | 39 | 2.18 | 33 | 8.63 | 39 | −1.08 | −0.37 | −0.57 | −0.91 | −0.81 | −0.98 |
| IR55419-04 | 3.17 | 7 | 1.49 | 7 | 2.05 | 2 | −0.58 | 0.8 | 1.12 | −0.4 | 0.37 | 0.72 |
| IR64 | 2.72 | 34 | 2.31 | 35 | 4.85 | 33 | 0 | 0 | 0 | 0.17 | −0.43 | −0.4 |
| IR66873-R-11-1 | 2.57 | 35 | 2.35 | 36 | 7.47 | 38 | −0.03 | −0.05 | −0.36 | 0.14 | −0.48 | −0.77 |
| IR67469-R-1-1 | 2.16 | 37 | 3.29 | 38 | 4.86 | 34 | −0.68 | −0.85 | −0.14 | −0.51 | −1.28 | −0.55 |
| IR72667-16-1-B-B-3 | 3.00 | 20 | 1.57 | 12 | 2.4 | 11 | −0.59 | 0.64 | 0.8 | −0.41 | 0.2 | 0.39 |
| IR74371-3-1-1 | 3.04 | 15 | 1.81 | 28 | 2.79 | 22 | −0.19 | 0.48 | 0.69 | −0.02 | 0.05 | 0.29 |
| IR74371-46-1-1 | 3.05 | 13 | 1.77 | 27 | 2.55 | 15 | −0.29 | 0.49 | 0.81 | −0.12 | 0.06 | 0.41 |
| IR74371-54-1-1 | 3.14 | 9 | 1.56 | 10 | 2.52 | 13 | −0.34 | 0.81 | 0.81 | −0.16 | 0.38 | 0.41 |
| IR74371-70-1-1 | 3.30 | 2 | 1.75 | 26 | 2.72 | 19 | 0.13 | 0.77 | 0.85 | 0.31 | 0.34 | 0.44 |
| IR74371-78-1-1 | 3.20 | 6 | 1.69 | 21 | 2.83 | 23 | −0.03 | 0.76 | 0.72 | 0.14 | 0.33 | 0.32 |
| Kallurundaikar | 3.04 | 16 | 1.7 | 23 | 2.3 | 8 | −0.46 | 0.5 | 0.94 | −0.28 | 0.07 | 0.53 |
| Khiradhan | 2.72 | 33 | 2.18 | 34 | 6.65 | 37 | 0.12 | 0.18 | −0.26 | 0.29 | −0.25 | −0.66 |
| MTU 1010 | 2.94 | 23 | 1.85 | 30 | 3.36 | 29 | −0.17 | 0.43 | 0.4 | 0 | 0 | 0 |
| NDR 1098-6 | 2.77 | 29 | 1.45 | 6 | 2.95 | 24 | −0.88 | 0.66 | 0.36 | −0.7 | 0.23 | −0.04 |
| PM 1011 | 2.91 | 24 | 1.59 | 15 | 3.65 | 31 | −0.39 | 0.73 | 0.23 | −0.22 | 0.3 | −0.17 |
| PMK 1 | 2.23 | 36 | 4.04 | 39 | 5.96 | 36 | −0.24 | −0.98 | −0.23 | −0.06 | −1.42 | −0.63 |
| PMK 2 | 2.12 | 38 | 3.09 | 37 | 5.45 | 35 | −0.75 | −0.79 | −0.25 | −0.58 | −1.22 | −0.65 |
| Poornima | 2.74 | 32 | 1.57 | 13 | 2.39 | 10 | −0.97 | 0.39 | 0.65 | −0.79 | −0.04 | 0.25 |
| R1027-2282-2-1 | 2.81 | 27 | 1.69 | 22 | 3.83 | 32 | −0.42 | 0.53 | 0.16 | −0.24 | 0.1 | −0.24 |
| RF 5329 | 3.01 | 18 | 1.52 | 9 | 2.33 | 9 | −0.64 | 0.69 | 0.83 | −0.47 | 0.26 | 0.43 |
| RR 272-21 | 2.75 | 30 | 1.63 | 19 | 3.43 | 30 | −0.64 | 0.5 | 0.24 | −0.47 | 0.07 | −0.17 |
| Tripuradhan | 3.15 | 8 | 1.58 | 14 | 2.24 | 6 | −0.42 | 0.73 | 1.01 | −0.24 | 0.3 | 0.61 |

Note: The color scale of gradient backgrounds going from red to green represents the lower value of the index or ranking in red and the upper value in green. MYI, mean yield index; DYI, drought yield index.

# 4 Discussion

## 4.1 Selection based on YPSI and YSSI

Selecting genotypes for stress resilience based on high yield under both yield potential and stress conditions does not quickly identify the best drought-tolerant genotypes as this trait has complex genetic expression[8,22]. Thus, severe stress strongly decreases yield of most of these genotypes, with rare exceptions (A genotypes) having high and stable yields over a range of environments[31]. Since YPSI and YSSI are highly correlated to yield under irrigated and stress conditions, respectively (Fig. 1), they can accelerate this selection based on yield performance. In this case, selecting genotypes with YPSI and YSSI values superior or equal to the reference cultivars identified the same five genotypes irrespective of stress intensity. The YPSI and YSSI scoring scales more rapidly and easily highlights these genotypes based on their yield performance in both environments, compared to using the original yield values where thresholds may be more difficult to determine and represents a more arbitrary choice directly related to breeder expertise. Additionally, score index values are easily compared between different stress environments or environmental changes year to year, unlike the original yield values or original stress indices.

The key advantage of selection using YPSI and YSSI is based on analyzing the individual score indices of production and resilience capacity (PCI and RCI, respectively). This fine-tuning differentiates genotypes in terms of productivity and resilience to identify the best ones, while discarding those with lower resilience. This improves the conventional method based only on yield performance and previously recommended indices MP, GMP and STI, such as in Khodarahmpour et al.[24].

Most of the genotypes obtain a similar score (PCI and RCI) under severe stress compared to moderate stress. However, severe stress decreased the PCI and RCI of DSL 104-1 and the reference cultivars (IR64 and MTU 1010) to a greater extent than the mean yield reduction of the whole population. Additional stress will almost certainly continue to decrease yield of these genotypes. We agree with Raman et al.[26] who considered DGI 75 and IR74371-70-1-1 as improved lines (but we also include DGI 307), as they yield better than reference cultivars. However, when SI exceeded 0.32, ARB 8 becomes more productive than all other genotypes (Table 2, Table 3, and Fig. 2). Therefore, IR74371-70-1-1, DGI 75 and DGI 307 are not the highest-yielding genotypes under stress conditions but the highest-yielding genotypes under no stress that are better adapted to a range of stress environments than the reference cultivars. These genotypes should be considered as the best B genotypes observed in this trial but not A genotypes (Fig. 3(a,c) and Fig. S2(a,c)).

Basing selection on yield performance in both no-stress and stress environments tends to favor more genotypes with higher yield in no-stress environments resulting in lower PCI than RCI values. In fact, by first observing YPSI and YSSI and then PCI and RCI, we selected genotypes with the highest production capacity with good resilience (Table 4). Moreover, utilizing PCI and RCI identifies high-yielding genotypes in no-stress environments with poor stress resilience that can be discarded. The selected genotypes (i.e., the best B genotypes in this case) must be recommended for irrigated lowland conditions. As rainfed lowland ecosystems could sporadically suffer moderate drought stress, these genotypes will not be the best yielding ones if the SI exceeds their thresholds but are a better option than the reference cultivars (IR64 and MTU 1010). Indeed, the improved line IR4371-70-1-1 has been promoted throughout India (Dar et al.[8]), yielding better than IR64 under no-stress to moderate stress. Here we have demonstrated that ARB 8 is more productive from moderate to severe stress intensity but yields less under favorable conditions (Fig. 2).

Similarly, in aerobic systems with irrigation management, DGI 307, DGI 75 and especially IR4371-70-1-1 could be tested. However, greater physiologic knowledge, such as phenological susceptibility of these genotypes to drought stress, is needed to better control the stress intensity when reducing irrigation volume[17,32]. For example, identifying the most sensitive stages of these genotypes can help to adjust water management at those stages to minimize yield penalties.

Selection based on yield performance conceals genotypes with more stable yields that do best only under stress conditions (C genotypes). These genotypes, with better resilience mechanisms to maintain yield under stress conditions, such as drought avoidance (maintains its water status) and/or tolerance (decreased crop water), typically have lower yield under no-stress conditions and are therefore usually discarded by this kind of selection method. These C genotypes yield better under drought stress (e.g., for wheat genotypes in Pakistan[33]), but until now no straightforward method has been applied to detect them[34]. Direct selection based on PCI and RCI would allow breeders to easily distinguish genotypes with the best compromise between resilience and productivity under stress conditions, the best C genotypes and the A genotypes (when they are present) as these score values can be compared across stress intensities (Table 2 and Table 3) and years.

## 4.2 Selection based on PCI and RCI

Whether to use PCI and RCI as selection criteria depends on breeding objectives and the target rice ecosystem. For aerobic rice, breeders require high-yielding genotypes with high stress tolerance[10,17], previously classified as A genotypes[28]. However, rainfed lowland, aerobic rice and upland ecosystems all yielded less than irrigated lowland (paddy) ecosystems[17]. Without these rare A genotypes, the best C genotypes seem most adapted to these cropping systems. Ensuring reasonable high and stable yields (even if less than optimum conditions) seems a better strategy than risk having lower yield while trying to achieve the highest yield possible by expecting a favorable year.

The 11 common genotypes, with high resilience capacity and high yield in moderate to severe stress environments, are good candidates for these environments. However, they do not have the best performance under no-stress and low stress intensity, compared to others (IR74371-70-1-1, DGI 75 and DGI 307). Therefore, only the best genotypes in terms of PCI and RCI (ARB 8, IR55419-04 and ARB 7) should be recommended for moderate to severe stress environment such as rainfed lowland, upland and aerobic rice ecosystems, but not for irrigated lowland ecosystem. Nevertheless, some genotypes were best for more moderate environments, with IR4371-70-1-1 suitable for no to moderate stress such as irrigated lowland ecosystems to some low stress rainfed ecosystem.

Following the theoretical distribution of Thiry et al.[22], selecting genotypes with PCI and RCI values superior or equal to 7 should identify the A genotypes (Fig. 3(b)). Since ARB 8 had the best value of PCI and RCI across 39 rice genotypes, classifying it as an A genotype should be considered. ARB 8 was not common to both suggested selection methods (1, YPSI-YSSI + PCI and RCI. or 2, PCI and RCI only), therefore is best considered as the best C genotype in this panel.

Introducing a hypothetical pure A genotype into the data set (Fig. S2(b,d)) redistributes the genotypes within the groups (A to D) and demonstrates that PCI and RCI can more easily discriminate A genotypes from B and C as previously suggested[22]. However, using this method in the absence of A genotypes within the population distinguishes C from B and D, thus the best-performing C genotypes.

Without A genotypes in a trial (the most likely situation), using score indices to fine tune the selection to the target environment identifies genotypes: (1) those with high yields under no to moderate stress (fine-tuning PCI-RCI after YPSI-YSSI selection method) or (2) those better adapted to moderate to severe stress environment (direct selection on PCI and RCI). The first method selects the best B genotypes that tolerate some stress, but increased stress decreased their yield more markedly (Fig. 2). These genotypes are ideal for areas with no stress to mild drought such as under irrigated lowland ecosystem and rainfed lowland under favorable conditions. The second method identifies the best C genotypes (closer to the A genotypes; Fig. 3(b)) that perform better than the best B genotypes with increased stress (from moderate to severe stress; Fig. 2). These should be selected for drought prone areas such as rainfed lowland, upland and aerobic rice ecosystems. In this case, one genotype (ARB 8) performed better than all other genotypes when SI exceeded 0.32 (moderate stress) (Fig. 2).

Crossing genotypes from both selections, corresponding to the best B and C genotypes, may create pure A genotypes. Some crosses with these genotypes include: (1) using IR55419-04 as a donor parent for drought tolerance in different crosses such as IR55419-04/2*TDK1[35,36] or Super Basmati and IR55419-04[18], and (2) other panels with ARB 8 and ARB 7[37].

However, the literature does not contain information on crosses between these best B genotypes (IR4371-70-1-1, DGI 75 and DGI 307) and the best C genotypes (ARB 8, IR55419-04 and ARB 7). Nevertheless, IR74371-70-1-1 is already a backcross between IR55419-04 and Way Rarem (IR55419-04*2/Way Rarem)[38].

## 4.3 Comparing with Raman selection

In 2012, Raman et al.[26] aimed to identify high-yielding rice lines in a range of environments from yield potential to drought stress. Some genotypes (IR4371-70-1-1 and DGI 75) were selected based on better yield performance in all environments than the reference cultivars IR64 and MTU 1010 (giving positive deviation; Table 6) within the top three based on the MYI. Their selection ranked all genotypes from 1 to 39 from the highest to the lowest index value. Although genotype ARB 8 ranked first by MYI, their selection excluded it due to the negative deviation with local cultivars (IR64 and MTU 1010) under irrigated conditions (Table 6). In contrast to our conclusions, ARB 8 was not considered the best option for variable rainfall patterns with equal probability of normal, moderate or severe stress occurring[26].

To determine the threshold that limits the best genotypes, the score index method is more straightforward than the commonly-used original index ranking as in Raman et al.[26]). Choosing the top 3, 5 or 7 genotypes seems arbitrary, and values are not comparable over stress intensity or years. To solve this problem, they[26] determined this limit by using the yield deviation compared to local cultivars but this method tends to favor high-yielding genotypes in no-stress environments, like examining the yield performance in no-stress and stress environments. Logically they settled on IR4371-70-1-1 and DGI 75, with high MYI and positive deviation of yield under all conditions compared to the local cultivars. Fernandez[28] observed the same tendency with tolerance indices such as STI, MP or GMP, which are usually recommended to identify genotypes with high yield in both no-stress and stress environments[22]. This was confirmed using YPSI and YSSI based on yield performance. However, the YPSI-YSSI method associated with PCI-RCI fine-tuning identified DGI 307 with good yield potential and similar resilience under moderate and severe stress compared to IR4371-70-1-1. In this case, the score index method saved some genetic biodiversity, but may also discard genotypes.

While our analysis of yield performance highlighted the same genotypes (Fig. 4) as Raman et al.[26], our recommendations differ. ARB 8, IR55419-04 and ARB 7 are better options to enhance production and resilience to greater future stress intensities in rainfed lowland, upland and even aerobic ecosystems.

To demonstrate the consistency of the score index selection method along different years or trials, another 36 genotypes from Verulkar et al.[29] were selected, including the six genotypes we selected using both methods and same two reference cultivars (Supplementary Section A). Two of the three selected genotypes with each method were common to both panels[26,29], demonstrating the feasibility of selecting genotypes under stress conditions by comparing their yield responses in terms of resilience and productivity to the response of the whole population (PCI and RCI). Therefore, applying the score index method in long-term, larger field experiments should improve genotype selection within breeding programs[34].

Identifying high-yielding genotypes is one of the elements of the Green Revolution, which saved millions of lives by increasing crop yields. High-yielding genotypes usually need abundant resources such as water, mineral fertilizer and agrochemicals, as these were often inappropriately used, it reduced the “green” impact of that revolution[39]. In response to climate change, it is now imperative to save resources such as water while maintaining or increasing food production. Simultaneous climate-induced harvest failures in major crop-producing regions have been demonstrated to pose a significant threat to food supplies worldwide[9]. Therefore, the

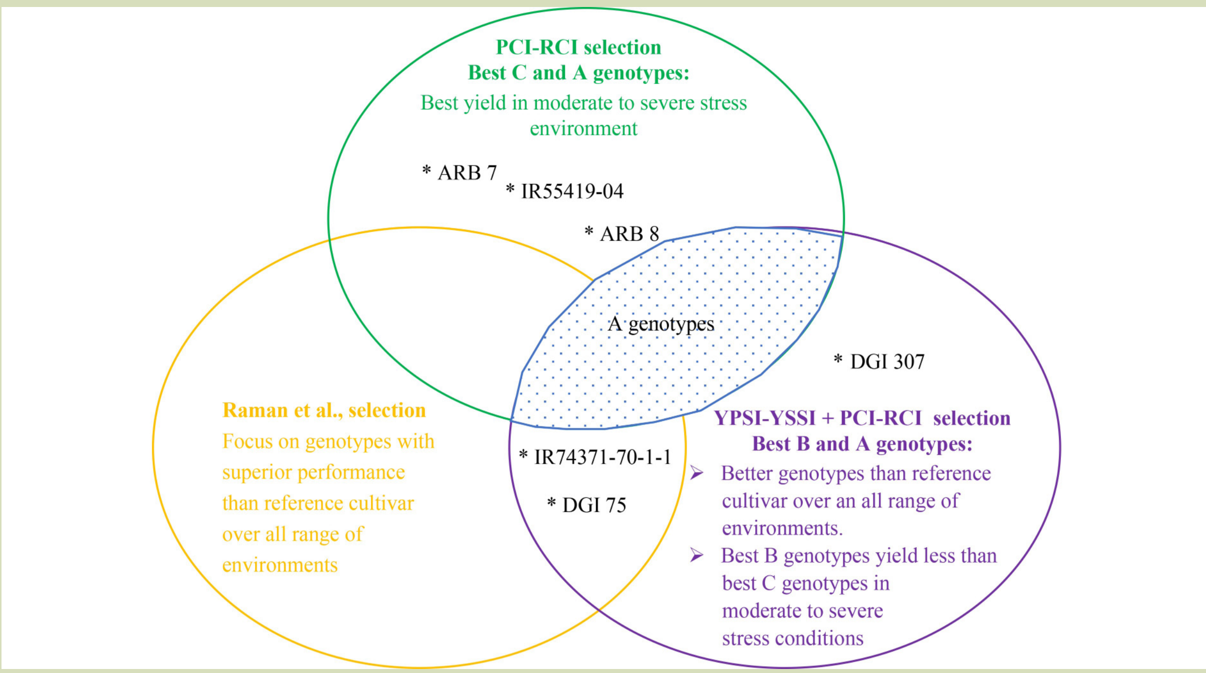


**Fig. 4** Summary of the genotype selection as a function of each method presented and discussed in this paper.

sustainability of food production in Asia, particularly in China, is critically linked to global food security, as it feeds one-fifth of the global population[40]. In this context, we believe that the techniques described in this paper are an important contribution.

## 5 Conclusions

Using the score index method can easily discriminate the best adapted genotypes for specific target environments such as rainfed lowland, aerobic rice and upland ecosystems. Genotypes with consistent score indices (PCI, RCI, YPSI and YSSI) were identified under different stress intensities and seasonal conditions, that were not detected using the original indices (SSI, TOL, MP, GMP and STI). Incorporating selection on PCI and RCI within breeding programs is recommended to better interpret the susceptibility and yield performance of different genotypes in a range of stress environments.

### Supplementary materials

The online version of this article at https://doi.org/10.15302/J-FASE-2023521 contains supplementary materials (Sections A–C; Figs. S1–S2; Tables S1–S3).

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### Compliance with ethics guidelines

Arnauld Thiry, William J. Davies, and Ian C. Dodd declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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