Received: 3 July 2023 | Accepted: 11 January 2024 | Published online: 13 February 2024

DOI: 10.1002/csc2.21197

Crop Science

ORIGINAL ARTICLE

Crop Breeding & Genetics

Seed yield and quality of interspecific hybrids of *Paspalum plicatulum* × *P. guenoarum* at different harvest times

Carolina Scienza | **Júlio Antoniolli** | **Júlia Longhi** | **Letícia W. Dias** | **Diógenes Cecchin Silveira** | **Rodrigo Sampaio** | **Victor S. de Ávila** | **Luis A. Escosteguy** | **Carine Simioni** | **Roberto Luis Weiler** | **Miguel Dall'Agnol** | **André Pich Brunes**

Faculdade de Agronomia, Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil

Correspondence
Júlia Longhi, Faculdade de Agronomia, Universidade Federal do Rio Grande do Sul, Porto Alegre, Rio Grande do Sul, Brazil.
Email: julialonghi98@gmail.com

Assigned to Associate Editor Dr. Esteban Fernando Rios.

Funding information
Conselho Nacional de Desenvolvimento Científico e Tecnológico; Associação Sul-Brasileira para o Fomento de Pesquisa em Forrageiras; Fundação de Amparo à Pesquisa do Estado do Rio Grande do Sul; Coordenação de Aperfeiçoamento de Pessoal de Nível Superior

Abstract

Paspalum guenoarum is a warm-season perennial grass, with a caespitose growth habit. The species is native to southern Brazilian grasslands and has been used in interspecific hybridizations because of its high palatability, resistance to trampling and grazing, and cold tolerance. Previous studies reported improvements in forage production and the nutritive value of hybrid material. However, there are limited data about seed production and seed quality of these hybrids. The aim of this study was to quantify the optimal time to harvest seed of three *Paspalum plicatulum* × *P. guenoarum* hybrids (08Q01, 104026, and 105052). Seed yield and seed quality were determined. Hybrids were harvested at 10, 20, and 30 days after flowering and evaluated for the components of seed yield, vigor, and viability. The optimum time to harvest was 20 days after the beginning of flowering. A >50% yield reduction, due to seed shattering, occurred when harvesting was delayed beyond 20 days. Harvesting <20 days after flowering resulted in a high percentage of empty spikelets and seeds with low vigor and viability. About 75% of the seed shattering took place 10–20 days after flowering, and for the 104026 and 105052 hybrids, >50% of seed was during this period. Hybrid 105052 had superior seed yield (2380 ± 280 kg ha^{-1}) and similar seed quality. These two characteristics, among others, are the most important ones when recommending a new commercial cultivar for release.

1 | INTRODUCTION

Paspalum guenoarum is a perennial warm-season grass with a caespitose growth habit, which is highly palatable to grazing cattle (Nabinger & Dall'Agnol, 2019). This species occurs naturally in the grasslands of southern Brazil, Argentina, and Paraguay, and it is also used as cultivated pasture in Australia, the United States, and Argentina, places where commercial cultivars have already been released (Aguilera et al., 2011).

Abbreviations: G28, germination after 28 days; G7, germination after 7 days; GSI, germination speed index; ID, inflorescence density; MES, mass of empty seeds; PCA, principal components analysis; PSY, pure seed yield; SPI, seeds per inflorescence; SPR, seeds per raceme; SY, seed yield; TSW, 1000-seed weight; VH, viability of harvest seeds; VS, viability of shattered seeds.

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.
© 2024 The Authors. *Crop Science* published by Wiley Periodicals LLC on behalf of *Crop Science* Society of America.

The main characteristics that make it an interesting forage plant for breeding new cultivars are cold and drought tolerance, high palatability and digestibility, and reliable forage production throughout the year, which can result in potential dry matter yields >18 t h^{-1} $year^{-1}$ (Minski Da Motta, Dall'agnol, Rios, Lopes De Souza, Weiler, Simioni, et al., 2020; Minski Da Motta, Dall'agnol, Rios, Lopes De Souza, Weiler, Brunes, et al., 2020; Pereira et al., 2012). *Paspalum guenoarum* has apomictic reproduction, which is considered an advantageous trait to multiply superior genotypes through clones, including hybrids, but with the formation of viable seeds (Kandemir & Saygili, 2015). This eliminates segregation in the progenies, thus maintaining desired characteristics (Carneiro et al., 2006; Kandemir & Saygili, 2015).

No sexual individuals have yet been found in this species (Novo et al., 2019; Ortiz et al., 2020). However, within the genus *Paspalum*, it is possible to carry out both intraspecific and interspecific crosses due to the diversity of reproduction modes and ploidy levels (Ortiz et al., 2020). *Paspalum guenoarum* belongs to the Plicatula group, in which most species are polyploid (tetraploid) and reproduce asexually (Novo et al., 2017). The utilization of a diploid ecotype of *P. plicatulum*, capable of sexual reproduction, made interspecific crossings possible through the artificial duplication of its chromosomes (Aguilera et al., 2011; Sartor et al., 2009). Subsequently, *P. plicatulum* and *P. guenoarum* have been used in interspecific hybridizations (Aguilera et al., 2011; Novo et al., 2017). Agronomic performance studies have shown that the hybrids obtained have the genetic potential for high dry matter yield (19,074 kg ha^{-1}), cold tolerance (Motta et al., 2017), and beef cattle preference for grazing (Novo et al., 2017). However, there are limited data for seed production and seed quality of these hybrids.

The challenges related to seed production in forage plants were described by Boonman (1971). Issues include uneven vegetative growth and transition to the reproductive phase between plants within a population, irregular and continuous flowering, poor little formation of inflorescences, and a reduction in the quantity and length of inflorescences formed at the end of the reproductive cycle. Additionally, harvestable seed yield (SY) and seed viability are compromised when a low number of seeds are formed and when there are high losses due to the seed shattering before harvest (Maity et al., 2021). In forage grasses, seed production losses can reach 50% (Herbage Seed Unit, 1994).

Identifying the optimal time for seed harvest is a challenge. When harvests are conducted too early, empty spikelets and malformed seeds are collected, resulting in reduced yield. Conversely, late harvests can result in low yields because potentially viable and vigorous seeds are lost by natural shedding. Thus, this work aimed to determine the optimal time to harvest seed for three hybrids of *P. plicatulum* × *P. guenoarum* evaluated in three harvest times, seed shattering, and also evaluate SY and its components as well as seed quality.

Core Ideas

- Native grass seeds are vital for sustaining livestock productivity in southern Brazil.
- There is a gap between seed yield and seed quality due to the harvest time in *Paspalum* hybrids.
- Delayed harvesting can halve seed yield, while early harvesting affects seed quality.
- Hybrids of *Paspalum plicatulum* × *P. guenoarum* are promising candidates for commercial cultivars due to seed traits.

2 | MATERIALS AND METHODS

2.1 | Experimental design and field management

The experiment was planted in October 2019 and evaluated for 2 years (2020 and 2021) at the agronomic experimental station of the Federal University of Rio Grande do Sul (UFRGS), Eldorado do Sul, RS, Brazil (30°05′S, 51°39′W, 34 m a.s.l.). The soil at the experimental site is a dystrophic ultisol, and the climate in the region is classified as subtropical humid (Cfa; Köppen classification). Monthly air temperatures generally followed the normal means (average of 30 years) excepted in September 2020, and the average of annual precipitation was ~1450 mm (Figure 1A,B).

Soil analysis was conducted from samples (0–0.2 m) taken in 2019 before starting the experiment. The soil pH (H_2O) was 5.7; P (c) was 8.1 mg dm^{-3}; K was 97 mg dm^{-3}; organic matter was 13.0 g kg^{-1}; Ca was 3.0 cmolc dm^{-3}; Mg was 1.2 cmolc dm^{-3}, and Al was not present at a toxic concentration. Lime and fertilizers were applied based on recommendations for C4 perennial grasses with an expected annual production of 16 t DM ha^{-1}, according to the Soil Fertility and Chemistry Commission—RS/SC guidelines (Sociedade Brasileira de Ciência do Solo SBCS, 2016). Filler-type limestone (relative total neutralizing power = 100%, fine particle size) was applied at a rate of 400 kg ha^{-1} to increase the pH to 6.0. Triple superphosphate and muriate of potash were applied at a rate of 30 kg ha^{-1} of P_2O_5 and K_2O, respectively.

The experimental design was a randomized block design in split-splot with three replications. Whole plot treatments were harvested three times—10, 20, and 30 days—after the beginning of flowering. That treatment was defined when 50% of florets were at anthesis regardless the number of tillers. Subplot treatments included three *Paspalum* interspecific hybrids (08Q01, 104026, and 105052). The hybrid 08Q01 was supplied by the Instituto de Botánica del Nordeste of the Universidad Nacional del Nordeste (IBONE/UNNE), Corrientes-Argentina. Hybrids 104026 and 105052 originated

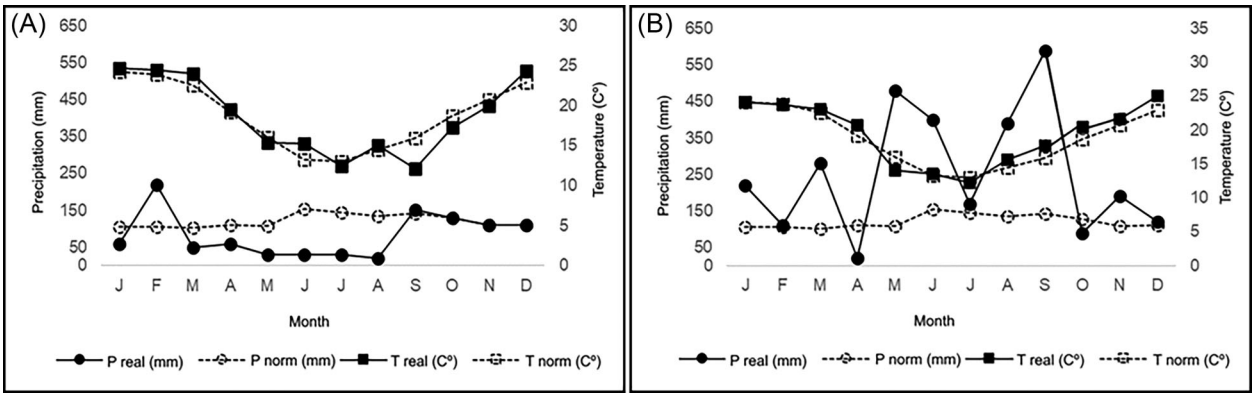


FIGURE 1 Mean monthly air temperature at 150 cm (°C) and total monthly rainfall (mm) for (A) 2020 and (B) 2021 measured at Eldorado do Sul, RS, Brazil (30°05′S, 51°40′W, 46 m a.s.l.). *Note*: Real = measured value in the field. Norm = average of the temperature and precipitation values over a 30-year period.

from crosses between the "4c-4x" induced sexual tetraploid genotype of *P. plicatulum* (Sartor et al., 2009) and the apomictic ecotype of *P. guenoarum* 'Azulão' (male parent) performed by Pereira (2013). All three hybrids were classified as obligated apomicts (Pereira, 2013) and presented a high forage yield potential, achieving up to 20 Mg of dry matter per year (Minski Da Motta, Dall'agnol, Rios, Lopes De Souza, Weiler, Simioni, et al., 2020; Minski Da Motta, Dall'agnol, Rios, Lopes De Souza, Weiler, Brunes, et al., 2020). Plants were grown from seeds and transplanted to the experiment site in October of 2019 in pure stands in six rows (7 plants row^{-1}) with a 0.3 m interrow spacing and 0.25 m interplant plants (3.15 m^2 plot size). Nitrogen (urea) was applied at a rate of 200 kg ha^{-1} in two split applications. The first application (80 kg ha^{-1}) was made after mowing, and the second (120 kg ha^{-1}) at the beginning of internode elongation. Weeds were removed by hand, and irrigation was applied at transplanting to promote establishment.



FIGURE 2 Inflorescences of *Paspalum guenoarum* hybrids are protected with a mesh sleeve made of fine tulle fabric to evaluate shattered seeds. Eldorado do Sul, Brazil, February 13, 2020.

2.2 | Data collection

Harvests were taken from February 29 to March 10, 2020, and from February 21 to March 11, 2021. Response variables were measured within a fixed 0.25 m^2 quadrat (0.5 × 0.5 m) placed in the center of each plot. Total shattered seeds were determined from five inflorescences protected with a mesh sleeve made of fine tulle fabric randomly distributed in the plot (Figure 2). From the samples collected in the quadrat, inflorescence density (ID), number of seeds per raceme (SPR), and number of seeds per inflorescence (SPI) were calculated. The total number of tillers was counted and visually separated into reproductive and vegetative groups. All inflorescences within the quadrat were harvested, comprising only the upper part of the canopy, dried to ~12% moisture, and manually threshed. The total weight of the threshed florets (filled + empty) was recorded as SY. Empty spikelet (ES) and other inert material were removed by blowing the seeds in a forced-air seed blower (South Dakota Seed Blower) to obtain the pure seed yield (PSY). The 1000-seed weight (TSW) was calculated from the average weight of eight subsamples of 100 filled florets multiplied by 10 (Brasil, 2009). Seeds were stored 4 months in a room at 15°C and 40% RH.

Seed germination was determined from four replications of 100 filled seeds from each plot. Samples were placed on KNO^3 (0.2%) solution-moistened filter paper in a plastic box named gerbox (Brasil, 2009). Plates were kept moist under controlled conditions in a growth chamber set to 16 h of light at 30°C and 8 h of darkness at 20°C. Germinated seeds were counted daily over a period of 28 days, and the germination speed index (GSI) was calculated by Maguire's (1962) formula: $M = n1/t1 + n2/t2 \ldots +nx/tx$, where $n1$, $n2$, … nx is the number of germinated seeds over $t1$, $t2$, … tx time elapsed

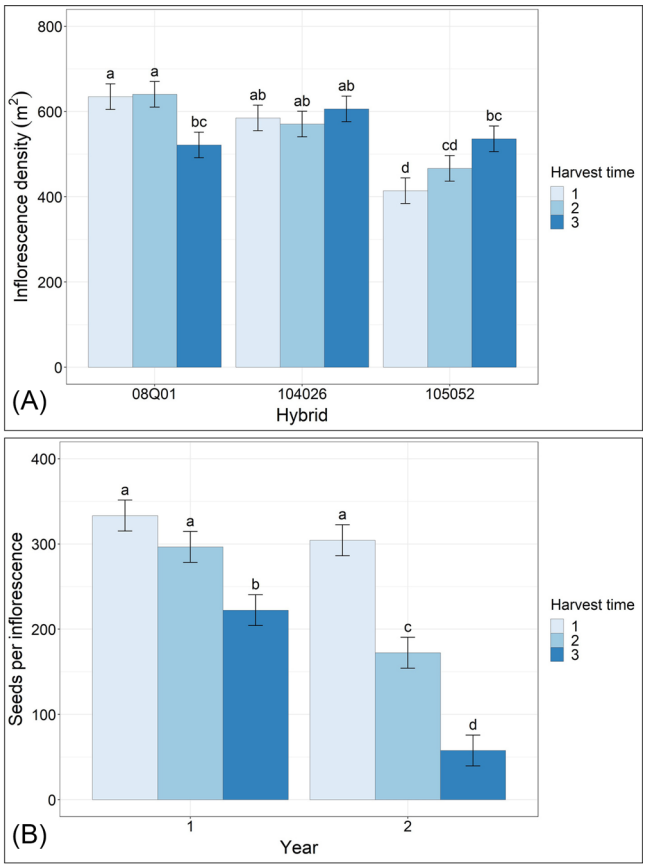


FIGURE 3 Inflorescence density (A) and seeds per inflorescence (B) for three hybrids of *Paspalum plicatulum* × *P. guenoarum* harvested at 10, 20, and 30 days after the beginning of flowering (1, 2, 3, respectively), evaluated in Eldorado do Sul, RS, Brazil at 2020 (year 1) and 2021 (year 2).

since the start of the experiment expressed in days. Germination was expressed as a percentage of normal seedlings obtained on day 7 (G7) and day 28 (G28).

Viable seed rate was estimated through the tetrazolium (TZ) test, carried out with four replications of 50 seeds per plot. Seeds were first presoaked in water for 16 h at 25°C, then were conditioned at 30°C and exposed to 2-3-5 triphenyl chloride of TZ (1%) for 24 h (Brasil, 2009), and then analyzed (Figure 3). This analysis was performed in viability of harvest seeds (VH) and in viability of shattered seeds (VS).

2.3 | Data analysis

All response variables were analyzed using linear models in R (R Core Team, 2021). Analysis of variance was performed by fitting a linear model with a split-plot treatment arrangement in a RCBD for all variables to test the statistical significance of the main factors and their interactions: year, block, harvest time, and hybrid. The graphs were created using the package ggplot2 in R (Vu, 2011). A Tukey HSD test was used to separate treatment means at $p < 0.05$ using the lsmeans package (Lenth, 2016) in R. Additionally, Pearson's correlation among traits was determined using the package stats (R Core Team, 2021).

To summarize the results obtained, principal component analysis (PCA) was performed. The analysis was performed after standardizing the data with mean of 0 and variance of 1. PCA was performed to condense the amount of information of the characteristics evaluated (Hair et al., 2009). Eigenvalues lower than 1 were omitted from the analysis as they did not have relevant information (Kaiser, 1958). The PCA was performed with the "factoextra" package in RStudio (R Core Team, 2021).

3 | RESULTS

3.1 | Seed yield components

ID was affected by the interaction between hybrid and harvest time ($p < 0.01$). At 10 and 20 days after the beginning of flowering, hybrid 105052 had 38% lower inflorescence production than 08Q01 and 104026, which had 440.4 ± 42.5 inflorescences m^{-2} (Figure 3A). By 30 days after the beginning of flowering, there was no difference among the hybrids 08Q01 and 105052 (529 ± 30 inflorescences m^{-2}), while the hybrid 104026 presented a higher ID of 606 ± 30. ID of 08Q01 decreased by 22% from 637.7 ± 42.5 at 10 and 20 days after the beginning of flowering to 521.7 inflorescences m^{-2} when harvested 30 days after the beginning of flowering. Conversely, the ID of 105052 increased from 414 m^2 when harvested 10 days after the beginning of flowering to 536 m^2 at the final harvest date. The ID of 104026 was unaffected by harvest time.

There was a significant effect for harvest time × year ($p < 0.01$) interaction on the SPI (Figure 3B). This interaction showed seeds/inflorescence were highest (315 ± 26), average from the harvest taken 10 days after the beginning of flowering and 20 days after the beginning of flowering in 2020. The lowest number of SPI was 58 ± 26 produced in 2021 from the harvest 30 days after the beginning of flowering.

The SPR was influenced by a year × harvest time interaction ($p < 0.001$; Figure 4A). Results indicated SPR ranged from a minimum of 17 ± 6 (Year 2 harvested 30 days after the beginning of flowering) to a maximum of 81 ± 6 from treatments harvested 10 days after beginning of flowering in both years and after 20 days in Year 1, on the average.

Seed shattering was affected significantly by three two-way interactions (hybrids × harvest time, hybrids × year, and harvest time × year). Seed shattering was higher in the second and third harvest times for the hybrids 08Q01 and 104026, while it was higher in the third harvest time for the hybrid 105052 ($p < 0.001$; Figure 4B).

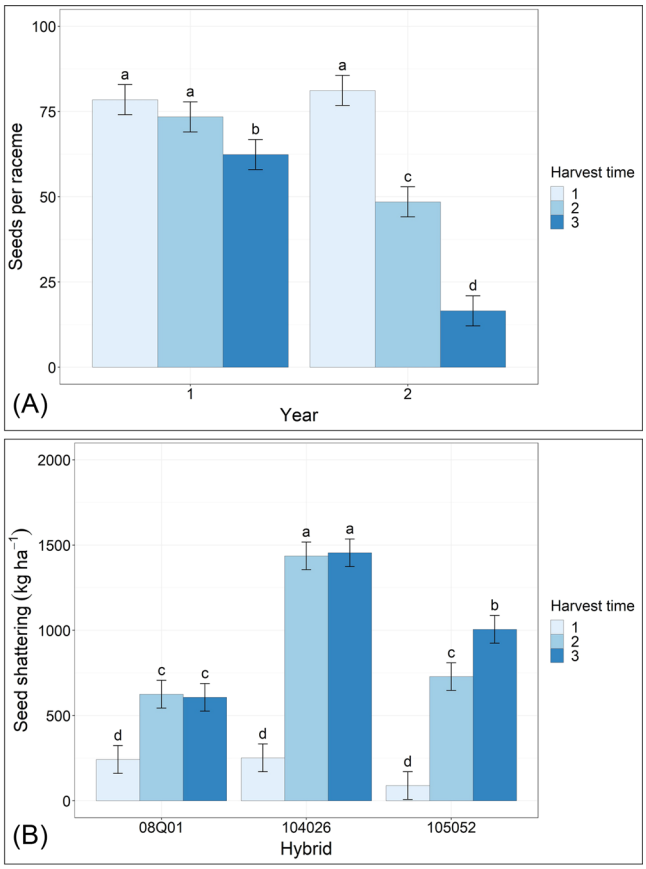


FIGURE 4 Seeds per raceme (A, year × harvest time interaction) and seed shattering (B, hybrid × harvest time interaction) for three *Paspalum plicatulum* × *P. guenoarum* hybrids harvested at 10, 20, and 30 days after beginning of flowering at Eldorado do Sul, RS, Brazil, in 2020 and 2021. The significance level was 5%.

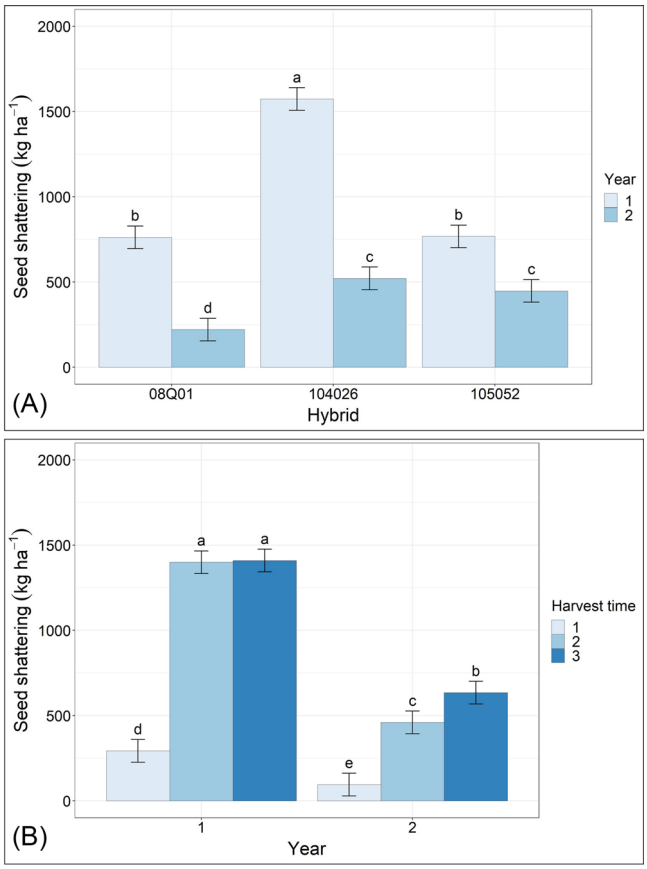


FIGURE 5 Seed shattering (A, hybrid × year interaction) and B (year × harvest time interaction) for three *Paspalum plicatulum* × *P. guenoarum* hybrids harvested at 10, 20, and 30 days after beginning of flowering at Eldorado do Sul, RS, Brazil, in 2020 and 2021. The significance level was 5%.

The hybrid × year interaction ($p < 0.001$; Figure 5A) showed seed shatter losses were higher in the first year of evaluation for all hybrids. However, the hybrid 104026 had higher losses than others (1574 ± 66.4 kg ha^{-1}). The lowest losses were observed for hybrid 08Q01 in the second year of harvest (221 ± 66.4 kg ha^{-1}).

Losses from seed shattering were 2.5 × higher in the hybrid 08Q01 when it was harvested 20 days after beginning of flowering compared with the first harvest at 10 days after the beginning of flowering (242.3 ± 81.3 kg ha^{-1}) at first harvest to 615.8 ± 81.3 kg ha^{-1} for the subsequent harvests. A similar result was observed for 104026, where losses by seed shattering increased from 251.4 ± 81.3 kg ha^{-1} at the first harvest to 1436.7 ± 81.4 kg ha^{-1} when harvested 20 days after the beginning of flowering, which was ~5.4x higher. For the hybrid 105052, the first harvest resulted in 10.5 × less seed-shattering losses than the last harvest at 30 days after the beginning of flowering (from 88.7 ± 81.3 to 1005.8 ± 81.3 kg ha^{-1}).

The year × harvest time interaction ($p < 0.001$; Figure 5B) showed that in the first-year treatment, means of the second and third harvest dates did not differ (mean of 1404.9 ± 66.4) and were superior to the first harvest (293.2 ± 68.8 kg ha^{-1}). In the second year, seed shattering increased over time, whose value was 95.1 ± 66.4 kg^{-1} at 10 days after the beginning of flowering and 634.8 ± 66.4 20 days later. It is worth noting that seed losses incurred by natural dehiscence after 20 days of the beginning of flowering were 2.5 × higher in the first year (1404 kg ha^{-1}) compared with the second year (547.7 kg ha^{-1}).

The 1000-seed weight (Figure 6) was affected by a hybrid × harvest time × year interaction ($p < 0.05$). In Year 1 (2020), there was a difference between the hybrids regarding TSW only for the first harvest time, in which 104026 was superior to 08Q01 (2.99 ± 0.18 and 2.34 ± 0.18), both not differing from 105052. In the second and third harvests, there were no significant differences between hybrids (2.61 ± 0.18). In the second year, the hybrid 104026 showed higher TSW than the others in the three harvesting times and higher TSW for this hybrid when it was harvested in the first period (3.67 ± 0.18).

The mass of empty seeds (MES) was also affected by a three-way interaction ($p < 0.01$). Generally, ES was highest at the first harvest and ranged from 1530 ± 308 kg h^{-1} for

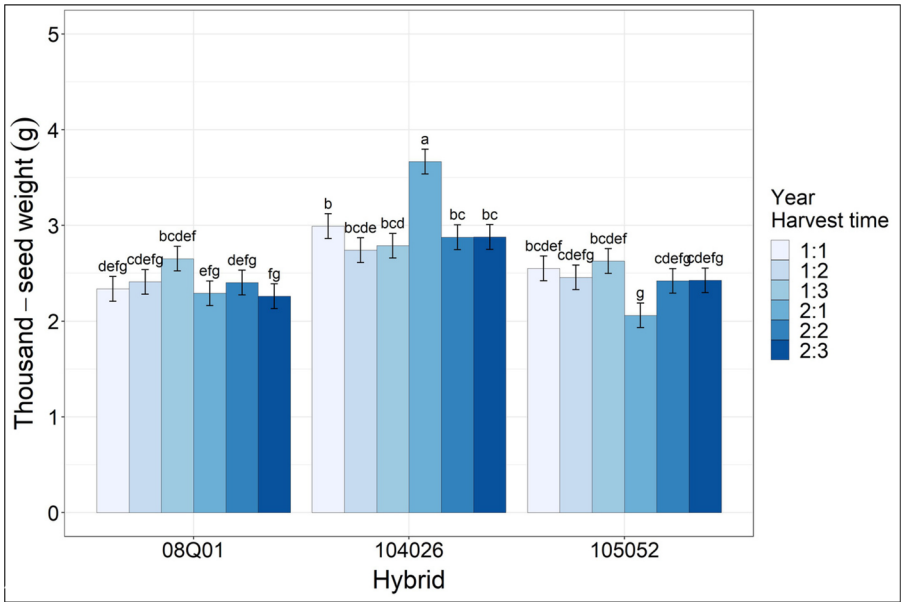


FIGURE 6 1000-Seed weight (g) (hybrid × harvest time interaction × year) for three *Paspalum plicatulum* × *P. guenoarum* hybrids harvested at 10, 20, and 30 days after beginning of flowering at Eldorado do Sul, RS, Brazil, in 2020 and 2021. The significance level was 5%.

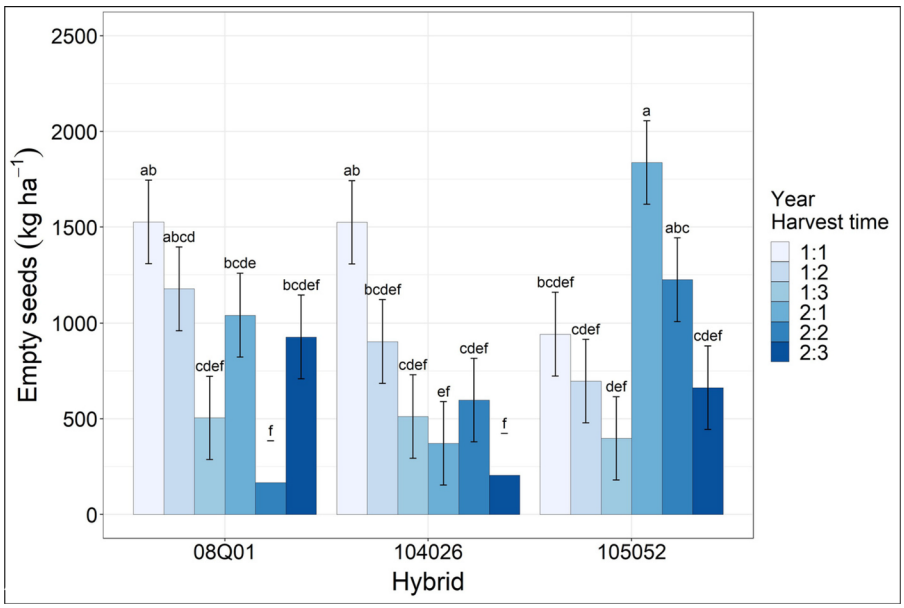


FIGURE 7 Empty seeds (kg ha^{-1}) (hybrid × harvest time interaction × year) for three *Paspalum plicatulum* × *P. guenoarum* hybrids harvested at 10, 20, and 30 days after beginning of flowering at Eldorado do Sul, RS, Brazil, in 2020 and 2021. The significance level was 5%.

08Q01 in Year 1 to 941 ± 308 for 105052 in Year 1 and from 1840 ± 308 for 105052 to 371 ± 308 for 104026 in Year 2 (Figure 7).

SY was affected by the two-way interaction between hybrid and year ($p < 0.001$; Figure 8). In the first year, hybrid SY did not differ among (1260 ± 280 kg ha^{-1}). In Year 2, SY of 105052 (2380 ± 280 kg h^{-1}) was 2.6 × more than the other hybrids.

PSY was affected by two two-way interactions. The year × harvest time interaction (Figure 9A) showed that in the first year, PSY declined ($p < 0.01$) from 1330 ± 127 kg ha^{-1} at the first harvest to 471 ± 127 kg ha^{-1} at the harvest 30 days after flowering. In the second year, PSY was 704.21 ± 127 and 765.90 ± 127 kg ha^{-1} for harvests taken 10 and 20 days after the beginning of flowering, which was ~55% more than PSY from the harvest 30 days after the beginning of flowering (455 ± 127 kg ha^{-1}).

The hybrid × year interaction ($p < 0.001$; Figure 9B) showed PSY of 08Q01 and 104026 (1030 ± 127 kg ha^{-1}) were superior to 105052 (678 ± 127 kg ha^{-1}) in Year 1. In

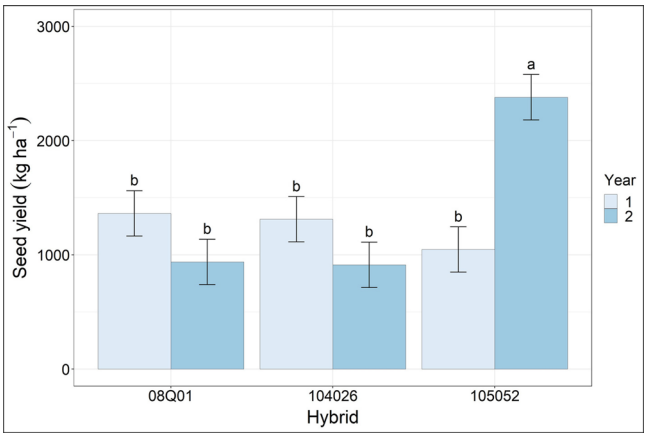


FIGURE 8 Seed yield (A, hybrid × year interaction) for three hybrids of *Paspalum plicatulum* × *P. guenoarum* harvested at 10, 20, and 30 days after beginning of flowering evaluated in Eldorado do Sul, RS, Brazil, during 2020 and 2021. The significance level was 5%.

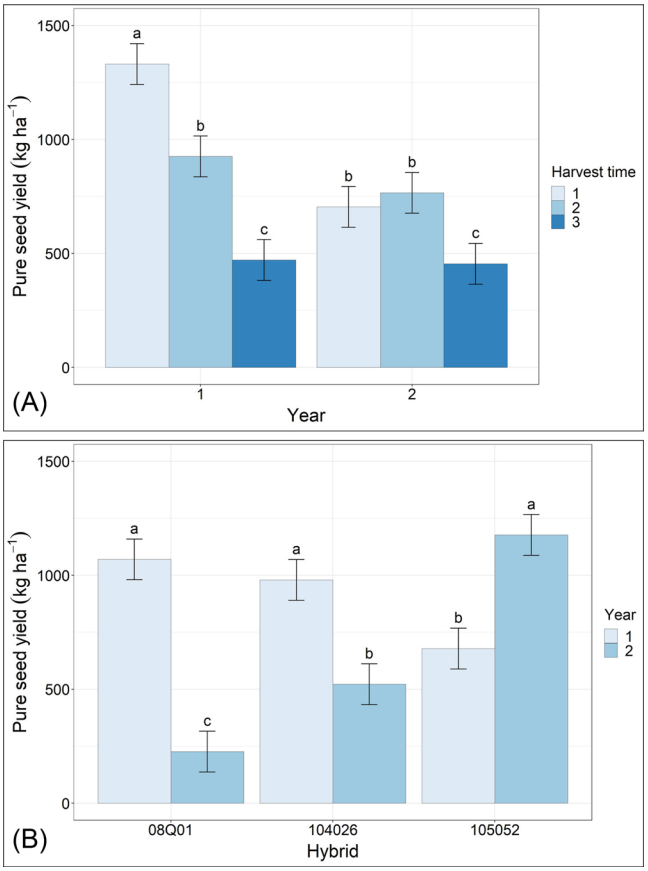


FIGURE 9 Pure seed yield (A hybrid × year interaction and B year × harvest time interaction) for three hybrids of *Paspalum plicatulum* × *P. guenoarum* harvested at 10, 20, and 30 days after beginning of flowering, evaluated in Eldorado do Sul, RS, Brazil, during 2020 and 2021. The significance level was 5%.

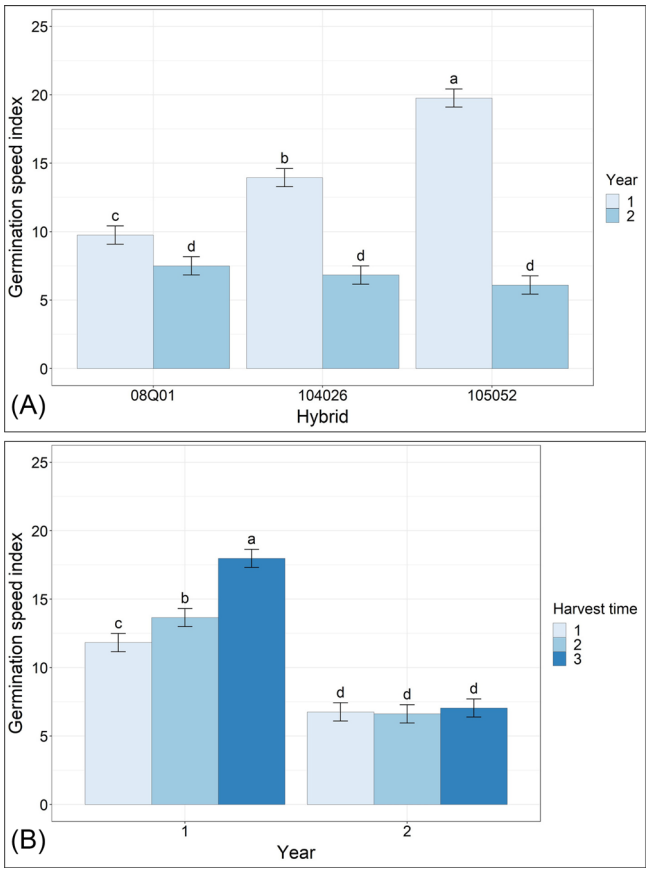


FIGURE 10 Germination speed index (A and B) evaluated by tetrazolium test for three hybrids of *Paspalum plicatulum* × *P. guenoarum* harvested at 10, 20, and 30 days after the beginning of flowering, evaluated in Eldorado do Sul, RS, Brazil, in 2020 and 2021.

the second year, 105052 had a PSY of 1180 ± 127 kg ha^{-1}, which was more than double that of 104026 (522 ± 127 kg ha^{-1}). The lowest PSY was from 08Q01 (226 ± 127 kg ha^{-1}).

3.2 | Seed quality

The GSI was influenced by two two-way interactions. Figure 10A shows the hybrid × year interaction ($p < 0.001$) where hybrid 105052 had the highest GSI (19.8 ± 0.94) and 08Q01 the lowest (9.75 ± 0.94). In the second year, there were no differences between hybrids (6.8 ± 0.94). Among the years × harvest time (Figure 10B), in the first year, GSI increased from 11.8 ± 0.94 to 18.0 ± 0.94 as harvest time was extended. However, in Year 2, GSI did not differ among harvest times (6.8 ± 0.94).

A three-way Hybrid × Harvest time × Year interaction ($p < 0.001$) affected germination after 7 days (G7; Figure 11) and germination after 28 days (G28; Figure 12). For G7, in the first year, 08Q01 and 105052 showed higher results when harvested 30 days after flowering. For this period, 105052 showed 56 ± 9.1% of germination against 36 ± 9.1% of the

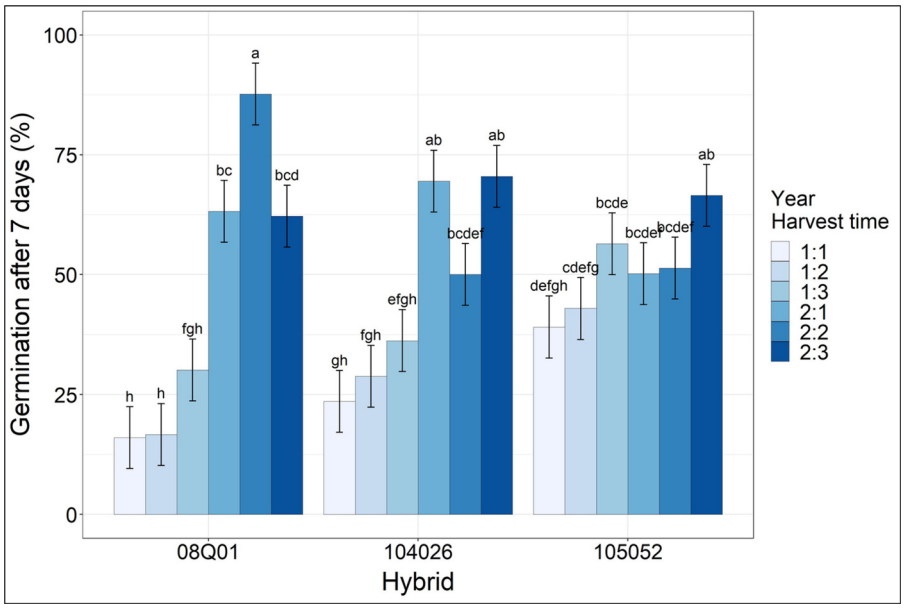


FIGURE 11 Germination after 7 days evaluated by tetrazolium test for three hybrids of *Paspalum plicatulum* × *P. guenoarum* harvested at 10, 20, and 30 days after the beginning of flowering, evaluated in Eldorado do Sul, RS, Brazil, in 2020 and 2021.

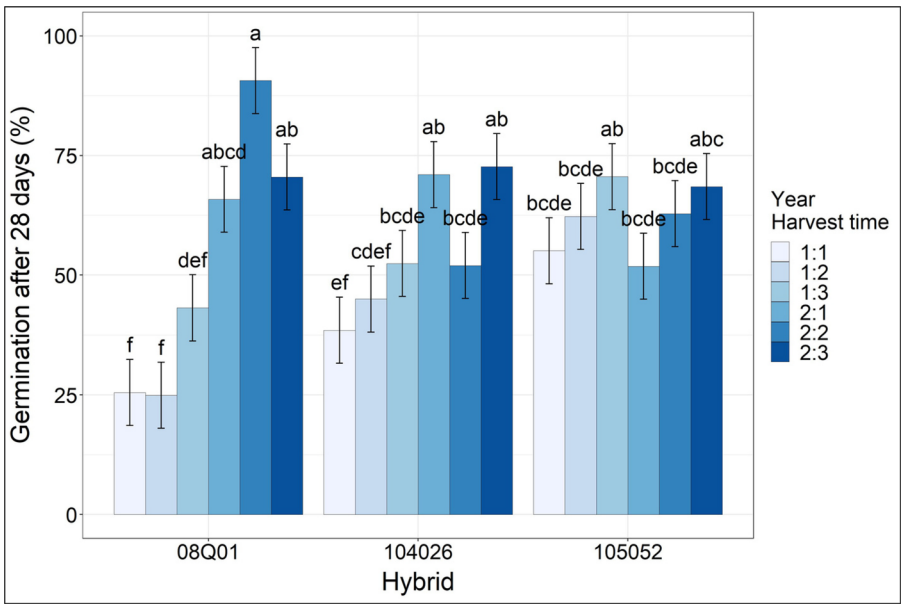


FIGURE 12 Germination after 28 days evaluated by tetrazolium test for three hybrids of *Paspalum plicatulum* × *P. guenoarum* harvested at 10, 20, and 30 days after the beginning of flowering, evaluated in Eldorado do Sul, RS, Brazil, in 2020 and 2021.

104026 and 30 ± 9.1% of the 08Q01. In year 2, the hybrids 08Q01 and 104026 showed a statistically higher average than in year 1, 71 ± 9.1% against 21 ± 9.1% for 08Q01 and 63 ± 9.1% against 30 ± 9.1% for 104026, and no differences were observed for 105052, being 56 ± 9.1% in year 2 against 46 ± 9.1% in year 1.

The three-way interaction affecting G28 showed a similar pattern of means separation to G7, except for hybrid 105052, which showed a stable behavior in the 2 years, where the percentage of germinated seeds increased as the seeds were harvested later, from 53 ± 9.7% in the first harvest time to 63 ± 9.7% in the third. Higher germination (91 ± 9.7%) was observed in the hybrid 08Q01 harvested 20 days after flowering in the second year, and the lowest results (25 ± 9.7%) occurred in this same hybrid when it was harvested 10 and 20 days after flowering in the first year.

Seed viability was evaluated in VH and VS. Both were affected by a hybrid × harvest time interaction ($p < 0.001$) for VH and ($p < 0.01$) for VS (Figure 13A,B). Each hybrid showed different results for VH, where 08Q01 had higher seed

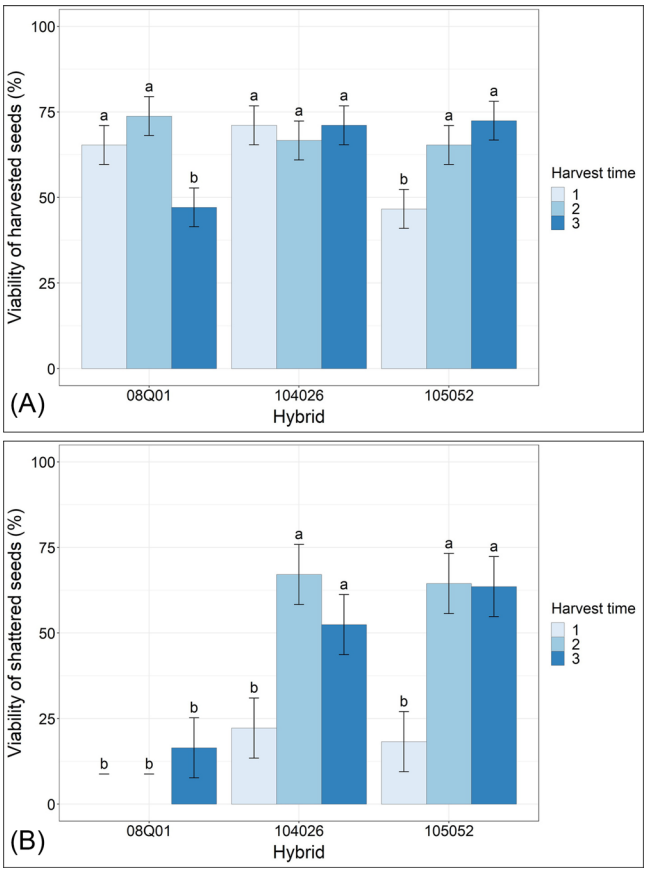


FIGURE 13 Viability of harvest seeds (A) and shattered seeds (B) evaluated by tetrazolium test for three hybrids of *Paspalum plicatulum* × *P. guenoarum* harvested at 10, 20, and 30 days after the beginning of flowering, evaluated in Eldorado do Sul, RS, Brazil, in 2020 and 2021.

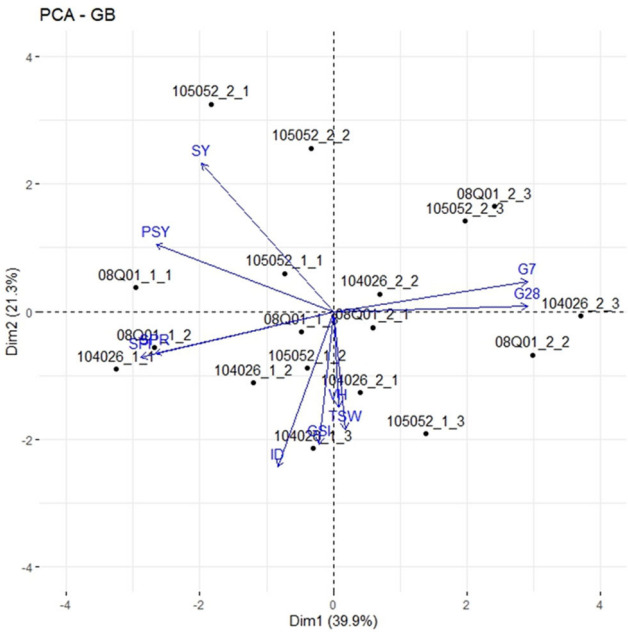


FIGURE 14 Principal components analysis (PCA) plot based on the first two principal components in three hybrids of *Paspalum plicatulum* × *P. guenoarum* harvested at 10, 20, and 30 days after beginning of flowering, evaluated in Eldorado do Sul, RS, Brazil, during 2020 and 2021.

viability when it was harvested at the first and second harvest times (71 ± 6.2%) and the lowest at the third harvest time (48 ± 6.2%). VH did not differ between harvest times for the hybrid 104026, being 69 ± 6.2% on average. For 105052, the VH was higher when the harvest occurred later, from 47% at time 1 to 74 ± 6.2% at time 3.

For VS, hybrid 08Q01 had no shattered seeds at the first and second harvest dates, but at the third harvest time, the shattered seed was 17 ± 9.4%. Note that 104026 and 105052 had similar values, with small rate of viable seeds in the first harvest time (average of 20 ± 9.4%) being higher at 20–30 days after flowering (average of 62 ± 9.4%).

The PCA based on the correlation matrix was performed to understand and summarize the associations between the treatments and traits studied. The results of the principal component analysis pointed to the first three PCs as usable to study the relationship between characters and treatments since the eigenvalues (λi) were greater than 1 (data not shown). The first two PCs explained 61.1% of the variance, with the first PC explaining 39.9% of the total variance, the second PC explained a further 21.3% of total variance, while the third PC explained 13.3% (Figure 14). Subsequently, the contribution and grouping of characters were verified. Characteristics associated with the physiological quality of seeds (G7 and G28) presented greater contribution in PC1 (Figure 14). For PC2, the performance-related traits (ID, SY, and TSW) had the greatest contribution. The graph clearly showed that the characters were grouped into four groups: 1: SY and PSY; 2: SPR and SPI; 3: TSW, TZVH, GSI; and 4: G28 and G7.

4 | DISCUSSION

4.1 | Seed yield components

ID was influenced by the interaction of hybrid × harvest time (Figure 4A). When perennial grasses enter the reproductive phase, plants will have both vegetative and reproductive tillers present at the same time (Moore & Moser, 1995). Hybrid 104026 had almost all the tillers passed to the reproductive stage already, 10 days after the beginning of flowering. For 105052, ID increased with time from flowering, which could indicate that it has an additional flowering requirement in relation to the others. ID for 08Q01 decreased by 15%–21% 30 days after flowering compared with harvests made at 10 and 20 days after flowering. The result was unexpected but was observed in both years, with a 21% reduction in the first year and a 15% reduction in the second year (data not shown), requiring further study. No year effect was observed for ID because this is a character highly influenced by genetics, and the environment had less influence because the experiment

was conducted in an artificially homogenized area. For *Paspalum dilatatum*, Barrios et al. (2015) found >80% heritability for panicle production curves. However, although this is considered the main component of SY for warm-season perennial grasses (Lopes & Franke, 2011), it did not ($p = 0.66$) influence PSY in this study.

The presence of a significant simple effect and higher variances for year and hybrid ($p < 0.05$) demonstrated that this character is highly influenced by these factors. For example, 2020 was higher than 2021 in terms of ID. The results obtained by Barrios et al. (2015) for *P. dilatatum* corroborate ours, in which >80% of the variation obtained was genetic for panicle production curves. However, although this is considered the main component of SY for warm-season perennial grasses (Lopes & Franke, 2011), it did not ($p = 0.66$) influence PSY in this study. The SPI was affected by hybrid × harvest time, hybrid × year, and year × harvest time interactions and did not had a significant correlation with PSY ($p < 0.644$ and $r = 0.06$). The SPI refers to the spikelets effectively retained in the inflorescences, although they may be empty. For all hybrids evaluated, the SPI decreased from the first to the third harvest (Figure 4B,D). This represents losses due to the detachment of seeds from the raceme over time due to either physiological maturity or environmental factors (wind and rain) between the end of February (harvest 2) and the beginning of March (harvest 3). In Year 1, all hybrids at all harvests had more seeds retained in the inflorescences compared to Year 2 (Figure 4C). Rainfall within the harvest period in Year 2 total ± 350 mm, which was 700% more than what occurred during the harvest period in Year 1 (±50 mm; Figure 1A,B). However, in the 2 years of evaluation, the SPI values were 200% higher than those of *P. guenoarum* ecotype Azulão (88–143) reported previously by Souza (2015).

The number of SPR reflects how much each raceme contributed to seed production within an inflorescence. This variable was influenced by the year × harvest time interaction (Figure 4A) and had no significant Pearson's correlation to the PSY ($r = 0.27$). In both years, the average number of seeds per raceme was followed the same pattern as SPI and decreased over time as seeds fell before harvest. Except for harvest 3 in Year 2 (57.7), all hybrids had higher SPR than those obtained by Souza (2015) with the Azulão ecotype (19 and 25 seeds per raceme in zero and one cut regimes, respectively).

Despite the three-way interaction observed for the TSW, there was little variation across years and harvest times (Figure 4B). Considering the 2 years of evaluation, the TSW had the lowest value (2.06 g) for the hybrid 105052 in the first period of the second year and the highest (3.67 g) for 104026 in the same period and in the same year. In general, the hybrid 104026 showed the highest TSW, but this did not result in superiority of yield or quality for this hybrid. These features were emphasized by Lopes et al. (2019) for presenting high heritability ($h^2 > 0.80$) in hybrids of *P. plicatulum* Michx. × *P. guenoarum* Arech, but this characteristic did not present a significant correlation with the yield ($r = 0.49$) nor with any variable related to the physiological quality of the seeds. The values found for this characteristic are close to those of the interspecific hybrids of *P. guenoarum* cv. Rojas × *P. plicatulum* (Aguilera et al., 2011) and are intermediate to the parents.

There was a significant ($p < 0.001$) and positive ($r = 0.73$) correlation between ES and PSY, so the highest PSYs are obtained when many empty spikelets are still present in the sample, and a high percentage of these is not related to low hybrid SY. In general, the MES decreased for all hybrids when the harvest was delayed. This was due to the gradual filling of the seeds and, consequently, a higher percentage of seeds that reached physiological maturity. The significant ($p < 0.001$) and negative ($r = -0.50$) correlation of ES with germination corroborates this.

For the three hybrids studied, most of the shattered seeds had already shed 20 days after flowering, except for 105052, which presented 26% more shattered seeds in the third harvest (996 kg ha^{-1}) compared with the second harvest (732 kg ha^{-1}; Figure 5D). In the genus *Paspalum*, it is reported that losses from seed shatter can reach 50% of the seeds produced (Maity et al., 2021). This agrees with the results found in this research when the harvest is delayed to 30 days after flowering. Despite this considerable loss, there was no significant correlation of this variable with the PSY ($r = 0.35$) since more seeds were filled during maturation. Seed shattering is an inherent characteristic of forage plants, and, despite being controlled by genes, it is highly influenced by environmental conditions (Maity et al., 2021). Therefore, strong winds, lodging, and time-dispersed seed production contribute to seed losses, which means harvestable SYs are usually below potential (Boonman, 1971; Elgersma, 1985). High temperatures and below average rainfall occurred in the first year (Figure 1A). This may explain why the seed shattering was almost three times greater in Year 1 compared to Year 2 (Figure 5F). High temperature conditions during reproductive transition can also induce early flowering (Maity et al., 2012; Pope et al., 2013) and may result in early seed or fruit shedding (Maity et al., 2021).

The higher quantity of empty seeds in the early harvests (Figure 5C) and the higher losses due to seed shattering in the later harvests (Figure 5D–F) explain why total SY was unaffected by harvest time (Figure 6A). The only difference in SY was obtained for the hybrid 105052 harvested in the second year, when it produced 2.6 times more. This is especially important when purity parameters are not established for commercialization and farmers can sell their seeds with a high percentage of impurities. In Brazil, the legislation allows *P. guenoarum* seeds with 60% purity to be sold commercially (Brasil, 2009). This means up to 40% of the material purchased by weight is not seed. Although legally acceptable, subsequent germination and establishment of that seed are also affected when immature seeds are included in the seed

purchased. A correlation ($r = -0.36$) was found between SY and G28. Although it was not considered high, it was very significant ($p > 0.007$) and indicated the presence of many malformed seeds with low germination potential. There was a tendency to reduce the number of empty seeds harvested in the second and third harvest times for the hybrids 08Q01 and 105052 in the 2 years of evaluation and only in the first year for the hybrid 104026. This reduction was on average 62% for hybrids 104026 and 105052 and 44% for hybrid 08Q01.

PSY is the most important component of the yield since all impurities are removed. The hybrid × year interaction showed that there was an inversion in the behavior of hybrids between years (Figure 7B). While 08Q01 and 104026 produced around 1000 kg seed ha^{-1} in the first year, 105052 produced only 678 kg ha^{-1}. In the following year, this same hybrid produced more than 1 Mg, while 104026 and 08Q01 produced only 522 and 226 kg ha^{-1}, respectively. These results were like those found by Lopes et al. (2016), where Azulão produced 850 kg ha^{-1} in Year 1 and 719 kg ha^{-1} in Year 2. However, increased seed production in the second year is not often reported for tropical grasses.

Sward age has a strong effect on *Paspalum* SY, and greater seed production has been observed in the first year of production. Previous research on *P. plicatulum* (Chadhokar & Humphreys, 1973) and *P. notatum* (Rios et al., 2020) showed most of the response variables, except seed weight, exhibited significantly better performance during the first year of production. Therefore, productive behavior over time requires more research.

The harvest time × year interaction (Figure 6C) indicated PSY declined 87.8% by the third harvest date. If SY is lower, the physiological quality of the seeds increases considerably, so that significant correlations ($p < 0.001$) of −0.59 between PSY and G28 and of −0.57 between PSY and G7 were found.

4.2 | Seed quality

The physiological quality of seeds is measured by germination and vigor tests and is directly related to the ability to establish and form a pasture in a wide range of environmental conditions. Vigor was evaluated by GSI and G7, both related to the ability of the seed to germinate quickly and colonize the environment. In the first year, 105052 had a higher GSI than the other hybrids, but not in the second year (Figure 7A). It also happened in the interaction year × harvest time, where in the first year, the last harvest resulted in seeds with high vigor but, in the second year, all harvests resulted in seeds with similar performance (Figure 7B).

There was also a tendency to higher vigor evaluated by G7 in seeds harvested later in the first year (Figure 7C), where a higher percentage of seeds germinated early was observed in 105052, harvested 30 days after flowering. In the second year, this trend was observed only in the 105052 hybrid, while the other two presented variable behavior.

Germination at 28 days (G28) had similar results (Figure 7D). In Year 1, G28 of hybrids 08Q01 and 104026 increased as harvest time was delayed but only reached 50% germination, the minimum value for commercialization of *P. guenoarum* seeds in Brazil (2008), while 105052 had >60% germination regardless of harvest time in both years.

The TZ test results showed the seed viability rate was >50% (Figure 7E), whereas G28 seed viability was <50% for the hybrids 08Q01 and 104026 (Figure 7D). In Year 1, the air temperature was 2° higher than the long-term mean, while rainfall was 50% less than average (Figure 1A). This contributed to low germination rates on G7 due to seed dormancy, probably caused by the climate conditions that occurred (Figure 1A). These conditions during the reproductive phase have been associated with the production of more hard seeds in species including dallisgrass (*Paspalum dilatatum*) (Pearson & Shah, 1981) and wind millgrass (*Chloris cucullata* Bisch. and *Chloris subdolichostachya* Muell.) (Herrera et al., 2008). This is also supported by the lack of a year effect in the TZ analysis because the test detects seed viability regardless of seed dormancy. Physical dormancy has been reported to cause slow establishment in *Paspalum* species (Adkins et al., 2002) because the outer covering structures and/or caryopsis coats limit water uptake (Simpson, 2007). In panicoid grasses, these structures are even more likely to impede germination because the coleorhiza must emerge through a rigid lemma by opening a hinged flap named the germination lid (Haaret al., 2014).

The TZ also verified that shattered seed from hybrids 104026 and 105052 harvested more than 20 days after flowering had >50% viability (Figure 7F). It was not possible to carry out the test on the seeds of the hybrid 08Q01 in the first two harvest times, as no shattered seeds were present. However, the shattered seeds collected at 30 days after the beginning of the flowering showed a low percentage of viability.

PCA analysis grouped hybrids 08Q01 and 105052 in the first year and harvest time, and hybrid 105052 in the second year, during the first and second harvest time around the PSY and SY characters (Figure 8). The analysis confirmed the results presented in Figures 4–6, where the highest number of seeds was obtained in the first year and where SY decreased as harvest time increased from 10 to 30 days after flowering (Figure 8). The characters associated with physiological seed quality (G7, G28, GSI, and TZ) were more associated with hybrids 08Q01 and 104026 in the second year at harvest 20–30 days after flowering (Figure 8).

The results indicate that there is a balance between (1) harvesting later to obtain better quality seeds, but with greater losses by natural dehiscence, or (2) harvesting earlier for higher yields, but with a higher percentage of empty spikelets and immature seeds with low vigor and viability.

The quantification of these factors can help seed growers decide on the most appropriate time to harvest.

Therefore, these results showed the higher SY and quality of the hybrids, which have already presented high forage yield potential.

5 | CONCLUSIONS

The best harvest time for SY and quality was 20 days after the beginning of flowering. After this, SY can decline by >50% due to seed shatter. Harvesting 10 days after the beginning of flowering included a high percentage of empty spikelets and seeds with low vigor and viability.

About 75% of seed shattering occurred 10–20 days after the beginning of flowering, and for 104026 and 105052, the seeds fallen in this period present a percentage of viability greater than 50%.

All the hybrids could be recommended for release, although the hybrid 105052 presented the best combination of seed yield and seed quality.

AUTHOR CONTRIBUTIONS

Carolina Scienza: Project administration; supervision; writing—original draft. **Júlio Antoniolli**: Project administration; supervision; writing—original draft. **Júlia Longhi**: Data curation; visualization; writing—review and editing. **Letícia W. Dias**: Methodology; validation. **Diógenes Cecchin Silveira**: Data curation; formal analysis; software. **Rodrigo Sampaio**: Investigation; writing—review and editing. **Victor S. de Ávila**: Investigation; writing—review and editing. **Luis A. Escosteguy**: Investigation; writing—review and editing. **Carine Simioni**: Conceptualization; supervision; writing—review and editing. **Roberto Luis Weiler**: Conceptualization; supervision; writing—review and editing. **Miguel Dall' Agnol**: Conceptualization; funding acquisition; resources; supervision; writing—review and editing. **André Pich Brunes**: Conceptualization; formal analysis; funding acquisition; investigation; methodology; project administration; supervision; writing—review and editing.

ACKNOWLEDGMENTS

The author thanks the CAPES (Brazilian Federal Agency for Support and Evaluation of Graduate Education), CNPq (Brazilian Council for Scientific and Technological Development), FAPERGS (Research Support Foundation of the State of Rio Grande do Sul), and the South-Brazilian Association for the Promotion of Forage Research (SULPASTO) for financial support and grants.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ORCID

Júlia Longhi https://orcid.org/0000-0002-6608-3836
Luis A. Escosteguy https://orcid.org/0009-0002-4329-2827
Carine Simioni https://orcid.org/0000-0002-0642-6980

REFERENCES

Adkins, S. W., Bellairs, S. M., & Loch, D. S. (2002). Seed dormancy mechanisms in warm season grass species. *Euphytica*, *126*, 3–20. https://doi.org/10.1023/A:1019623706427

Aguilera, P. M., Sartor, M. E., Galdeano, F., Espinoza, F., & Quarin, C. L. (2011). Interspecific tetraploid hybrids between two forage grass species: Sexual *Paspalum plicatulum* and apomictic *P. guenoarum*. *Crop Science*, *51*(4), 1544–1550. https://doi.org/10.2135/cropsci2010.10.0610

Barrios González, P., Speranza, P., Glison, N., Piccardi, M., Balzarini, M., & Gutiérrez, L. (2015). Analysis of flowering dynamics heritability in the perennial warm-season grass *Paspalum dilatatum*. *Grass and Forage Science*, *71*, 123–131. https://doi.org/10.1111/gfs.12159

Boonman, J. G. (1971). Experimental studies on seed production of tropical grasses in Kenya. 2. Tillering and heading in seed crops of eight grasses. *Netherlands Journal of Agricultural Science*, *19*(4), 237–249. https://doi.org/10.18174/njas.v19i4.17304

Brasil. (2009). *Regras para análise de sementes*. MAPA/ACS. https://www.gov.br/agricultura/pt-br/assuntos/insumos-agropecuarios/arquivos-publicacoes-insumos/2946_regras_analise__sementes.pdf

Carneiro, V. T., Dusi, D. M., & Ortiz, J. P. (2006). *GSB SAMPLE © 2006 62 Apomixis: Occurrence, applications and improvements*. http://www.globalsciencebooks.info/Books/images/FOPBVolume1sample.pdf

Chadhokar, P. A., & Humphreys, L. R. (1973). Effect of tiller age and time of nitrogen stress on seed production of *Paspalum plicatulum*. *The Journal of Agricultural Science*, *81*(2), 219–229. https://doi.org/10.1017/S002185960005886X

Elgersma, A. (1985). Floret site utilization in grasses: definitions, breeding perspectives and methodology. *Journal of Applied Seed Production*, *126*, 50–54. https://ihsgorg.files.wordpress.com/2018/07/elgersma-1985-j-appl-seed-prod-3_50-54.pdf

Haar, M., van Aelst, A., & Dekker, J. (2014). Weedy adaptation in *Setaria* spp.: VIII. Structure of *Setaria faberi* seed, caryopsis and embryo germination. *Quantitative Methods*, *1403*, 1–16. http://arxiv.org/abs/1403.7096

Hair, J. F., Black, W. C., Babin, B. J., Anderson, R. E., & Tatham, R. L. (2009). *Análise multivariada de dados*. Bookman Editora.

Herbage Seed Unit. (1994). *Forage seed production: ILCA training manual*. International Livestock Centre. https://pdf.usaid.gov/pdf_docs/Pnaby052.pdf

Herrera-C, F., Ocumpaugh, W. R., Ortega-S, J. A., Lloyd-Reilley, J., Rasmussen, G. A., & Maher, S. (2008). Environmental influences on seed quality of windmillgrass ecotypes in south Texas. *Agronomy Journal*, *126*, 1205–1210. https://doi.org/10.2134/agronj2007.0195

Kaiser, H. F. (1958). The varimax criterion for analytic rotation in factor analysis. *Psychometrika*, *23*, 187–200. https://doi.org/10.1007/BF02289233

Kandemir, N., & Saygili, I. (2015). Apomixis: New horizons in plant breeding. *Turkish Journal of Agriculture and Forestry*, *126*(4), 549–556. https://doi.org/10.3906/tar-1409-74

Lenth, R. V. (2016). Least-squares means: The R package lsmeans. *Journal of Statistical Software*, *69*(1). https://doi.org/10.18637/jss.v069.i01

Lopes, R. R., Jaeschke Ost, H., Souza, C. H. L. De, & Franke, L. B. (2016). Management of consecutive cuts in the production and quality of wintergreen Paspalum seeds. *Revista Brasileira de Zootecnia*, *45*(10), 587–595. https://doi.org/10.1590/S1806-92902016001000002

Lopes, R. R., & Franke, L. B. (2011). Correlação e análise do coeficiente de trilha dos componentes do rendimento de sementes de grama-forquilha. *Revista Brasileira de Zootecnia*, *40*(5), 972–977. https://doi.org/10.1590/S1516-35982011000500005

Lopes, R. R., Franke, L. B., Souza, C. H. L. D., Bertoncelli, P., Graminho, L. A., Ávila, M. R. D., Pereira, E. A., & Motta, E. A. M. D. (2019). Genetic assessment of seed yield-related traits in superior hybrids of *Paspalum plicatulum* x *Paspalum guenoarum*. *Brazilian Journal of Animal Science*, *126*, e20190075. https://doi.org/10.1590/rbz4820190075

Maguire, J. D. (1962). Speed of germination aid in selection and evaluation for seedling emergence and vigor. *Crop Science*, *2*(1), 176–177. https://doi.org/10.2135/cropsci1962.0011183X000200020033x

Maity, A., Lamichaney, A., Joshi, D. C., Bajwa, A., Subramanian, N., Walsh, M., & Bagavathiannan, M. (2021). Seed shattering: A trait of evolutionary importance in plants. *Frontiers in Plant Science*, *12*, Article 657773. https://doi.org/10.3389/fpls.2021.657773

Maity, A., Chakravarty, S. K., & Yadav, J. B. (2012). Standardisation of hybrid seed production technology of first Indian mustard (*Brassica juncea*) hybrid NRCHB 506. *Indian Journal of Agricultural Sciences*, *82*, 753–758. https://doi.org/10.56093/ijas.v82i9.23828

Moore, K. J., & Moser, L. E. (1995). Quantifying developmental morphology of perennial grasses. *Crop Science*, *35*(1), 37–43. https://digitalcommons.unl.edu/agronomyfacpub/81

Motta, E. A. M. D., Dall'agnol, M., Pereira, E. A., Machado, J. M., & Simioni, C. (2017). Valor forrageiro de híbridos interespecíficos superiores de Paspalum. *Revista Ciência Agronômica*, *48*(1), 191–198. https://doi.org/10.5935/1806-6690.20170022

Minski Da Motta, E. A., Dall'agnol, M., Rios, E., Lopes De Souza, C., Weiler, R., Simioni, C., Brunes, A., Krycki, K., Graminho, L., Da Silveira Garcia, L., & Faraco Correa, A. (2020). Nutritive value and herbage mass in hybrids of *Paspalum plicatulum* × *Paspalum guenoarum* fertilized with nitrogen or in mixture with temperate legumes. *Grassland Science*, *66*(9), 261–270. https://doi.org/10.1111/grs.12280

Minski Da Motta, E. A., Dall'Agnol, M., Rios, E. F., Lopes de Souza, C. H., Weiler, R. L., Brunes, A. P., Simioni, C., Rockenbach de Ávila, M., Neto, D., Felix, L. D., & Nunes dosSantos, T. (2020). Agronomic performance of interspecific hybrids under nitrogen fertilization or mixed with legumes. *Agrosystems, Geosciences & Environment*, *3*, e20127.

Nabinger, C., & Dall'Agnol, M. (2019). *Guia para Reconhecimento de Espécies dos Campos Sulinos*. Ibama. https://doi.org/10.1017/CBO9781107415324.004

Novo, P. E., Galdeano, F., Espinoza, F., & Quarin, C. L. (2019). Cytogenetic relationships, polyploid origin and taxonomic issues in *Paspalum* species: Inter- and intraspecific hybrids between a sexual synthetic autotetraploid and five wild apomictic tetraploid species. *Plant Biology*, *21*(2), 267–277. https://doi.org/10.1111/plb.12931

Novo, P. E., Acuña, C. A., Quarin, C. L., Urbani, M. H., Marcón, F., & Espinoza, F. (2017). Hybridization and heterosis in the Plicatula group of *Paspalum*. *Euphytica*, *213*(8), Article 198. https://doi.org/10.1007/s10681-017-1983-4

Ortiz, J. P. A., Pupilli, F., Acuña, C. A., Leblanc, O., & Pessino, S. C. (2020). How to become an apomixis model: The multi-faceted case of *Paspalum*. *Genes*, *11*(9), 974. https://doi.org/10.3390/genes11090974

Pearson, C. J., & Shah, S. G. (1981). Effects of temperature on seed production, seed quality and growth of *Paspalum dilatatum*. *Journal of Applied Ecology*, *18*, 897–905. https://doi.org/10.2307/2402380

Pereira, E. A., Barros, T., Volkmann, G. K., Battisti, G. K., Silva, J. A. G. D., Simioni, C., & Dall'agnol, M. (2012). Variabilidade genética de caracteres forrageiros em *Paspalum*. *Pesquisa Agropecuária Brasileira*, *47*(10), 1533–1540. https://doi.org/10.1590/S0100-204x2012001000017

Pereira, E. A. (2013). Melhoramento genético por meio de hibridizações interespecíficas no Grupo Plicatula—Gênero Paspalum [Genetic improvement through interspecific hybridizations in the Plicatula Group—Paspalum genus] (Doctoral dissertation). Programa de Pós-Graduação em Zootecnia, Faculdade de Agronomia, Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil. Federal University of Rio Grande do Sul Digital Repository. https://www.lume.ufrgs.br/handle/10183/85404

Pope, K. S., Dose, V., Da Silva, D., Brown, P. H., Leslie, C. A., & Dejong, T. M. (2013). Detecting nonlinear response of spring phenology to climate change by Bayesian analysis. *Global Change Biology*, *19*(5), 1518–1525. https://doi.org/10.1111/gcb.12130

R Core Team. (2021). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org/

Rios, E. F., Zilli, A., Kenworthy, K. E., Mackowiak, C., Quesenberry, K., & Blount, A. (2020). Managing forage and turf-type bahiagrass for seed production. *Crop Science*, *60*(3), 1569–1579. https://doi.org/10.1002/csc2.20146

Sartor, M. E., Quarin, C. L., & Espinoza, F. (2009). Mode of reproduction of colchicine-induced *Paspalum plicatulum* tetraploids. *Crop Science*, *49*(4), 1270–1276. https://doi.org/10.2135/cropsci2008.05.0270

Simpson, G. (2007). *Seed dormancy in grasses*. Cambridge University Press.

Sociedade Brasileira de Ciência do Solo (SBCS). (2016). *Manual de calagem e adubação para os estados do Rio Grande do Sul e de Santa Catarina*. Comissão de Química e Fertilidade do Solo – RS/SC. http://www.sbcs-nrs.org.br/docs/Manual_de_Calagem_e_Adubacao_para_os_Estados_do_RS_e_de_SC-2016.pdf

Souza, C. H. L. (2015). Produção e qualidade de sementes de Paspalum guenoarum Arech. ecótipo "Azulão" submetido a diferentes regimes de corte no segundo ano de cultivo. *Dissertação (Mestrado)—Programa de Pós-Graduação em Zootecnia, Faculdade de Agronomia*, Universidade Federal do Rio Grande do Sul, Porto Alegre. Federal University of Rio Grande do Sul Digital Repository. https://www.lume.ufrgs.br/handle/10183/128127 Access at: 01 fev. 2022

Vu, V. Q. (2011). *ggbiplot: A ggplot2 based biplot* (R package version 0.55). GitHub Repository. http://github.com/vqv/ggbiplot

How to cite this article: Scienza, C., Antoniolli, J., Longhi, J., Dias, L. W., Silveira, D. C., Sampaio, R., de Ávila, V. S., Escosteguy, L. A., Simioni, C., Weiler, R. L., Dall'Agnol, M., & Brunes, A. P. (2024). Seed yield and quality of interspecific hybrids of *Paspalum plicatulum* × *P. guenoarum* at different harvest times. *Crop Science*, *64*, 697–709. https://doi.org/10.1002/csc2.21197