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Research article

Physiological and harvestable maturity of seeds in finger millet [*Eleusine coracana* (L.) Gaertn.]

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Abstract

Identification of correct stage of physiological maturity (PM) and ideal stage of harvestable maturity (HM) of seeds in finger millet is important for production of quality seed. The earliest date of appearance of seed setting was considered as the first stage of harvest and subsequently eight harvests were made at weekly intervals. The seeds harvested at different intervals during two late post-rainy seasons of 2019 and 2020 were evaluated. The study revealed the seed PM at 37 DAA (days after anthesis) during the first year for the variety VL347. The next harvest at 44 DAA reduced the seed yield, vigour and storability traits significantly indicating suitable stage of HM at 40 DAA. More or less similar, the second year results also confirmed these stages of PM and HM in VL347. In case of VR936, maximum seed quality reached at harvest stage of 48 DAA, however it was non-significant at 41 DAA for most of these traits, and further the seed yield reduced significantly with later harvest at 48 DAA. These observations indicated the appropriate stage of PM at 41 DAA and possible HM at 44 DAA in VR936. Also, the predictions based on polynomial regression model (II order) more or less closely confirmed these stages of PM in VL347 and VR936. The morphological indices observed at PM and HM stages were that most of the plants and ears appeared in brown to dark-brown and the seeds in brown to copper color. The black layer depression developed at hilum region of seed that was prominently visible at PM stage. These indicators help to judge the right stage of crop harvest for quality seed production in finger millet.

Keywords: Finger millet, Harvestable maturity, Morphological indices, Physiological maturity, Polynomial regression, Quality seed yield

Introduction

Finger millet is the third most important millet crop after pearl millet and sorghum, grown in many states of southern, central, eastern, western and northern India, from sea level in coastal Andhra Pradesh to 8000 feet altitude in the Himalayas. Finger millet cultivation as a food and forage crop is more widespread in terms of its geographical adaptation compared to other millets. It has the ability to withstand a wide range of environmental conditions, also thrives well and is very adaptable at higher elevations compared to most other tropical cereals. It is a staple food crop in the drought-prone areas of the world and is an important component for food security. Finger millet is highly valued for grain, while the stover is an excellent source of fodder for livestock. The finger millet grain is rich in calcium content (250–350 mg/kg), which is 20 to 30 times higher as compared to any other cereal. In addition to the advantage of finger millet for sustainability and human dietary food, this crop is also a good source of highly nutritious forage for livestock in several African and Asian countries. Recent research on finger millet forage highlighted its important features of adaptability, forage potential and nutritive value (Gowda *et al.*, 2015; Baath *et al.*, 2018; Kumar *et al,* 2021). In India, the dry stover after harvest of finger millet panicles is used as nutritious fodder for livestock in drylands. Apart from India, the straw is also used as forage in USA, Africa and Ireland. In comparison to fodder maize and sorghum, finger millet forage is rich in nutrients like calcium, phosphorus, and potassium and contains 61% of total digestible nutrients, 105 to 156 g kg^{-1} crude protein, 598 to 734 g kg^{-1} neutral detergent fiber, 268 to 382 g kg^{-1} acid detergent fiber, 597 to 730 g kg^{-1} in vitro digestibility, and 387 to 552 g kg^{-1} neutral detergent fiber digestibility (Backiyalakshmi *et al.*, 2021).

In India, finger millet is cultivated in an area of 1.1 million ha with a production of 1.58 million tons and average productivity of 1450 kg/ha. Karnataka state occupies the largest area (0.67 million ha) under finger millet, followed by Tamil Nadu (0.079 million ha), Maharashtra (0.086 million ha), Uttarakhand (0.095 million ha) and Odisha (0.041 million ha) (Bhat *et al.*, 2023). All India coordinated research programs so far released many improved varieties of finger millet for the benefit of the farming community. The seed plays a vital role as a carrier of the genetic potential of these improved varieties, and every farmer should be able to access quality seeds with high vigor and viability potential. During seed production, early and late harvest of seed crops leads to seed yield and quality losses. Early harvest with inadequate development of essential structures and protection mechanisms may result in poor quality (Ekpong and Sukprakarn, 2008). Mainly, the protection mechanisms develop during the late seed maturation phase, and the stage of harvest becomes the most critical factor for seed quality and storability (Jalink *et al*., 1998; Demir *et al*., 2008). Physiological maturity is the stage when the seed exhibits maximal dry matter with considerable seed moisture loss. At this stage, if maximal seed germination capacity and vigor are displayed, the seed can be harvested (Patrick and Offler, 2001). Sequential changes take place during seed maturation, right from fertilization to the cessation of nutrient supply to the seed from the mother plant (Marcos-Filho, 2015). Technologically, after the maturation process, the seed should complete the accumulation of maximum dry matter with enough moisture content and be capable of the highest germination and vigor (Araujo *et al*., 2006; Marcos-Filho, 2015). Different ways of determination of seed harvest maturity were reported in various crops based on seed dry weight and moisture content (Eskandari, 2012), seed germination traits (Ghassemi-Golezani and Hosseinzadeh-Mahootchy, 2009), accelerated aging and electrical conductivity (Samarah and Abu-Yahya, 2008; Vidigal *et al*., 2011), respiratory enzymes (Ramya *et al*., 2012) and mobilization of reserves (Oliveira *et al*., 2013).

The determination of the appropriate stage of harvestable maturity of seeds is a fundamental prerequisite in order to eliminate the seed deterioration in the field and consequent loss of yield and quality of seed. Thus, one of the important factors that affect the production of quality seeds and subsequent crop performance is the identification of the right stage of seed crop harvest. In finger millet, the scientific information on the effect of seed maturation on seed yield and quality traits at different stages of harvest is lacking and therefore, the present study aimed to identify the physiological maturity and optimum stage of harvest based on yield, physiological and biochemical quality traits of seeds.

Materials and Methods

Experimental material: The experiments were conducted during late post-rainy seasons at ICAR-Indian Institute of Millets Research (ICAR-IIMR), Hyderabad located at 17.3850°N, 78.4867°E and altitude of 505 m (India). The sowings were done on 7 January 2019 and 13 December 2019 in a completely randomized block design (CRBD) with three replications with two cultivars of finger millet (VL347 and VR936). However, due to late flowering in variety VR936, there was desiccation of pollen due to exposure to high temperature, which led to failure of seed setting during the first year so the data was collected with single variety VL347 only, and the seed formation required 9 days after anthesis (DAA) in VL347. The earliest date of appearance of seed setting was identified as the first stage of harvest (HS-I). Accordingly, eight harvests were made at weekly intervals *viz.,* at 9, 16, 23, 30, 37, 44, 51 and 58 days after anthesis (DAA) in VL347 during the first year. However, during the second year, the seed setting appeared at 17 DAA in VL347 and 20 DAA in VR936, which were considered as the first stages of harvest, respectively. Eight dates of harvest stages at weekly intervals were fixed at 17, 24, 31, 38, 46, 52, 59 and 66 days after anthesis (DAA) in VL347 and at 20, 27, 34, 41, 48, 55, 62 and 69 DAA in VR936 during the second year.

Seed yield, moisture content, hardness and test weight: At each stage of harvest, seed weight per plant was recorded from five randomly labeled plants, which was expressed in grams (g). The seed yield per net plot (6 sq. m) calculated per one hundred plants was expressed in kilograms (kg). Seed samples were freshly collected at each stage of harvest and evaluated for seed moisture content using a digital seed moisture meter (*FARMEX-MT-PRO, FARMCOMP, Agro-electronics, USA*) programmed specifically for millet seeds and the values were expressed in *percentage* of moisture content. The digital hardness tester (*Pharmag Instruments Ltd*., *India*) was used to measure the hardness of seeds. It works with a force gauge to measure the tension/ compression by applying the force on a single seed. The single seed hardness of ten randomly selected seeds per replication from four replicates of each sample was tested and the mean value was expressed in kilogram-force (*kgf*). From each sample of seed harvest, four replicates of a hundred seeds each were counted and weighed in mg for test weight expression.

Seed germination and vigor traits: The seed germination tests were conducted as per the rules of the International Seed Testing Association (ISTA, 2015) specified for finger millet. Germination counts were made on 8^{th} day and the seedlings were evaluated for growth and vigor traits. The germination percentage (G) was calculated based on the number of normal seedlings produced per 100 seeds. Ten normal seedlings were selected at random for recording seedling characters. Root length (RL) was measured from the collar region to the tip of the primary root and shoot length (SL) from the collar region to the tip of the first leaf. Seedlings with abnormal growth were separated. Seedling dry weight (SDW) was measured after drying the 10 normal seedlings in a hot air oven maintained at 80°C for 24 hours. The seedling vigor index (SVI) was calculated in two ways, *viz.*, multiplying mean germination percentage by seedling length (root + shoot) (SVI-I); and multiplying mean germination percentage by dry weight of single seedling (SVI-II) and the results (SVI-I and SVI-II) were expressed to the nearest whole numbers. The field emergence (FE) of fresh and accelerated aged seeds was tested by sowing the seeds in four replications, each of 50 seeds in cement pots (45 cm diameter) filled with red and black soils mixed in proper proportion. After 20 days, the seedlings that emerged out with leaves above the soil surface were counted and expressed in percentage.

Amylase enzyme activity in seedling: Dry seeds weighing 0.2 g were facilitated to germinate in petri plates with moistened filter paper. The samples were harvested at 3rd, 5th and 8th day of germination. The samples in triplicates were used to estimate the α-amylase activity assayed according to the procedure reported by Bernfeld (1955). The α-amylase activity was expressed as a number of micromoles of maltose released per minute by total enzyme extract from 100 seeds (µ moles of maltose released /minute /100 seeds).

Electrical conductivity test: One-gram seed from each harvest was weighed and then immersed in 100 mL deionized water at 25°C for 24 hours. The electrical conductivity of leachates of each replicate was measured by using a conductivity meter (*Systronics model-conductivity meter-306, India*) and conductivity per gram of seed weight was calculated (µS/cm/g) and recorded.

Storability of seeds using accelerated ageing (AA) test: The AA tests for seed were conducted in an 'Accelerated aging chamber (*Memmert-HPP 108/749, Germany*). The sampled seeds from each stage of maturation were subjected to accelerated aging. The seeds in a single layer were placed on stainless mesh racks inside the aging chamber to create a higher humidity of 90% or above at 44±1°C temperature during the test for required periods (as identified with prior standardization) specific to finger millet.

Statistical analysis: The data was transformed to arc-sine values wherever necessary, and ANOVA was performed in a randomized complete block design using a statistical software package (*Statistrix, version 8.1*). The polynomial regression models adjusted at second order (degree) were applied (*Microsoft Excel*) to predict the right stage of harvests to obtain maximal seed yield, vigor and storability traits. The figures were made using *Microsoft Excel*.

Results and Discussion

Seed moisture, hardness and yield: In VL347, the anthesis was completed at 83 days after sowing (DAS) during the first year, similarly during the second year at 82 DAS. In the case of VR936, it required 96 DAS to complete anthesis during post rainy season. Later, the seed development began and maturation continued until maximum dry matter accumulation with considerable moisture loss in the seed, *i.e.*, the stage of physiological maturity. However, this period varied between two varieties. The seed formation (setting) appeared at 9 days after anthesis (DAA) in I year and 17 DAA in II year with VL347 and 20 DAA with VR936, which was considered as the first stage of harvest that resulted mostly in immature seeds. The seed harvested at subsequent stages varied significantly for seed moisture content, hardness and seed yield traits with the advancement of seed maturation. Seed moisture declined gradually after 9 to 58 DAA (I year) and 17 to 66 DAA (II year) in VL347 and after 20 to 69 DAA in VR936 (Fig 1a; Table 1). The gradual reduction in seed moisture from harvest stage I to VIII was due to the moisture equilibrium that took place between the seed and its surrounding atmosphere. In contrast with a reduction in seed moisture, the seed hardness increased steadily and significantly in both cultivars (Fig 1a; Table 1). Leprince and Buitink (2010) defined desiccation tolerance as the ability of a living entity to deal with extreme moisture loss to levels below 0.1 g water per gram dry weight or drying to a relative humidity below 50%, and subsequent re-hydration without accumulation of lethal damage. Seed development shifts to the maturation phase after a series of cell divisions and cell differentiation that differ at early reserve accumulation and late maturation drying. Seed acquires desiccation tolerance during early maturation. At early stages of maturation, the mechanisms behind the onset of desiccation tolerance were activated in orthodox seeds (Leprince *et al*., 2017). Sequential changes occurred in the seed from fertilization until the seed turned independent from the mother plant due to the cessation of nutrient supply (Marcos-Filho, 2015). Technologically the matured seed exhibits enough moisture, maximum dry matter, high germination and vigor (Araujo *et al*., 2006; Marcos-Filho, 2015; Kannababu *et al*., 2023a; 2023b). In VL347, seed test weight increased from 9 to 37 DAA (I year) and 17 to 45 DAA (II year) and thereafter declined significantly until the final stages of harvests (Fig 1a). Seed test weight increased during 20 to 48 DAA (Table 1)

Table 1. Effect of seed maturation stages on seed yield and related traits in finger millet cultivars during post rainy season (2020)

Days after anthesis (DAA)		Seed moisture content (%)		Seed hardness (kgf)		Seed test weight (mg)		Yield/ plant (g)		Yield/ plot (g)	
VL347	VR936	VL347	VR936	VL347	VR936	VL347	VR936	VL347	VR936	VL347	VR936
17	20	13.8	14.8	1.41	1.44	203	228	13.9	12.6	1217	1183
24	27	13.1	14.4	1.48	1.51	208	243	18.6	15.1	1714	1504
31	34	12.8	13.8	1.55	1.57	214	254	18.9	20.7	1768	2237
37	41	12.2	13.3	1.60	1.63	221	265	22.6	20.3	2312	2025
45	48	11.8	12.8	1.66	1.72	241	281	20.4	16.7	2110	1847
52	55	11.3	12.3	1.73	1.81	230	269	18.8	13.5	1724	1652
59	62	10.8	11.8	1.79	1.87	222	253	17.2	11.1	1685	1372
66	69	10.4	11.3	1.83	1.95	210	245	16.5	11.1	1603	1217
CD*	CD*	*0.38*	*0.21*	*0.68*	*0.06*	*9.33*	*5.41*	*3.08*	*1.96*	*433*	*228.6*

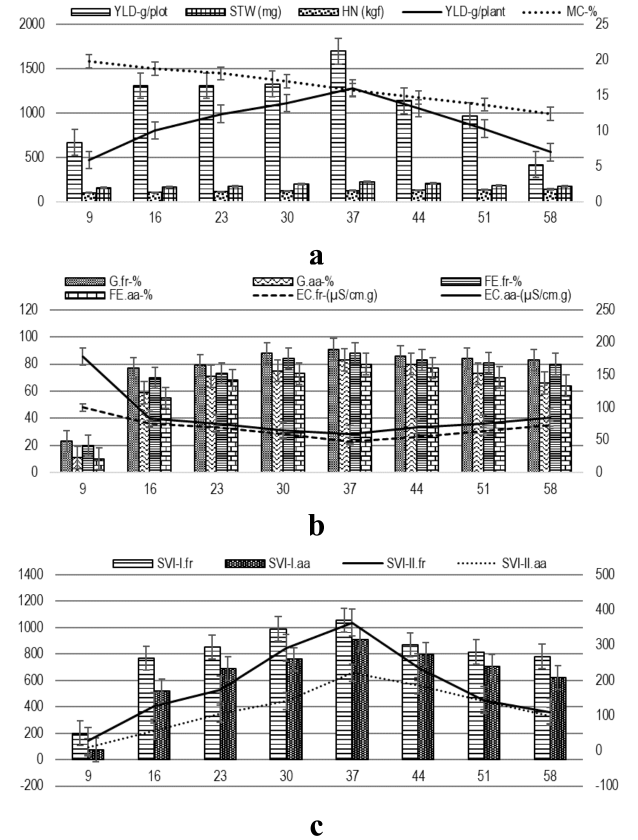

Fig 1. (a) Effect of different stages of seed maturation on seed moisture content (MC), hardness (HN), test weight (STW) and yield (YLD) traits in finger millet cultivar VL347; (b) Effect of different stages of seed maturation on seed germination (G), field emergence (FE) and electrical conductivity (EC) of fresh (fr) awnd accelerated aged (aa) seeds in finger millet cultivar VL347; (c) Effect of different stages of seed maturation on seedling vigour index (SVI-I & SVI-II) of fresh (fr) and accelerated aged (aa) seeds in cultivar VL347

in VR936. In VL347, steady and significant increases in seed yield per plant and plot were observed from the first stage of harvest, *i.e.*, 9 DAA to 37 DAA during I year (Fig 1a). A similar trend was observed during II year also, but with higher values of seed yield per plant and plot after 17 to 38 DAA (Table 1) with VL347. In VR 936, the seed yield per plant and per plot increased significantly after 20 to 34 DAA. However, further reduction in yield traits until 41 DAA was not significant. These results were in concurrence with the reports on kodo millet and barnyard millet (Kannababu *et al.*, 2023a; 2023b). Cultivar differences in seed yield and quality traits were also reported in forage sorghum (Kannababu *et al.*, 2015; 2021) and for seed yield in Indian oat (Shweta *et al.*, 2020). Similar to the results, the predictions based on the polynomial regression model also drew maximum seed yield per plant at 37 DAA (R^2=0.9659) during I year and 40 DAA (R^2 = 0.8035) in II year for VL347 and 40 DAA

(R^2=0.715) for VR936 (Fig 2). Accumulation of maximum dry matter in seed indicated physiological maturity (Harrington, 1972; Ma *et al.,* 2002), and this stage closely coincided with the formation of a dark closing layer in the placental area near sorghum kernel attachment (Maiti *et al.,* 1985; Tonapi *et al.*, 2006; Kannababu *et al.,* 2023a; 2023b). Similar to these reports, seeds and plants of finger millet exhibited specific morphological indices coinciding with the harvest stage when the maximum yield was noticed. The plants, ears and seeds appeared in brown to dark brown (copper) colors at physiological and harvestable maturity stages (Fig 3a). The black layer depression around the hilum of the seed is distinguishably visualized (Fig 3b). These morphological indices help to judge the right stage of harvest in finger millet for quality seed production. The end of the filling phase was termed mass maturity by Ellis and Pieta-Filho (1992) as the compromised definition of physiological maturity misleads.

Seed germination, vigor and storability: The germination, field emergence and seedling vigor of fresh seeds increased steadily with the advancement of seed maturity during 9 to 37 DAA in I year and 17 to 45 DAA in II year in VL347, whereas from 20 to 48 DAA with VR936. Later to these stages, most of the seed quality traits declined gradually and significantly. However, the decrease was non-significant between 37 to 44 DAA (I year), 38 to 45 DAA (II year) in VL347 for most of the seed quality traits, and between 41 to 48 DAA stages in VR936 for seed germination and seedling vigour-I. In the case of aged (AA) seeds, germination, field emergence, seedling vigor index-I and seedling vigor index-II increased steadily with the advancement of seed maturity from 9 to 37 DAA in VL347 (Fig 1b). Later in these stages, the seed quality traits declined significantly. Accelerated aging test estimated the seed storability potential of a seed lot by exposing the samples to high relative humidity and temperature (Delouche, 1973). The delayed harvest, even after seed maturation, led to seed deterioration in the field itself (Delouche, 1973). Black *et al*. (2006) described that physiological maturity is the stage at which a seed or the majority of a seed population reaches maximum vigor and viability. Similarly, Finch-Savage and Bassel (2016) defined the stage of physiological maturity to the point of maximum seed quality. High temperatures and drought at the anthesis and seed development stages led to the deterioration of seed quality in rice (Abdul-Rahman and Ellis, 2019) and soybean (Jumrani and Bhatia, 2018). The polynomial regression analysis for VL347 predicted maximum germination and seedling vigor for fresh (fr) and aged (aa) seeds between 37 to 44 DAA during I year (R^2=0.8169 for G.fr%, 0.9122 for G.aa%, 0.8582 for SVI-I.fr, 0.9503 for SVI-I.aa, 0.8431 for SVI-II.fr, and 0.8948 for SVI-II.aa). Further, the II year's data for VL347 showed similar predictions for fresh seed quality (R^2=0.8718 for G.fr%, 0.7483 for SVI-I.fr, and 0.7379 for SVI-II.fr) (Fig 2a, b, d, e). More or less similarly, the peak values of fresh seed germination and seedling vigor were predicted with a polynomial regression model between 40 to 45 DAA (R^2 = 0.8963 for G.fr%, 0.8908 for SVI-I.fr, and 0.76 for SVI-II.fr) in case of VR936 during 2020 (Fig 2d, f). The first and foremost factors that affect seed vigor, viability and storability are the harvesting conditions, as stated by Pollock and Roos (1972). The electrical conductivity (EC) (mhos/cm) values of fresh and aged seeds harvested at different stages of maturity showed higher values at the initial stage of harvest in VL347 and reduced significantly until 37 DAA (Fig 1b). Later to this stage, EC values increased significantly. However, the EC values of aged (aa) seeds were higher compared to fresh seeds, irrespective of stage of harvest. Loss of membrane integrity was the primary physiological event during the seed deterioration process as indicated by the EC test (Delouche and Baskin, 1973). The vigorous seeds are more capable of reorganizing the cell membrane compared to non-vigorous seeds with reduced integrity of the membrane as indicated through more leakage of electrolytes. In immature seeds subjected to desiccation before harvest are prone to leak more electrolytes during the initial germination process (ISTA, 1995). Deterioration of seed quality due to seed aging was reflected in an increase in electrical conductivity reduction in seed enzyme activity in sunflowers (Das and Biswas, 2022; Kannababu *et al.,* 2023a; 2023b). The reduction in α-amylase activity reflected this because both mitochondria (essential for energy production), and the endoplasmic reticulum (vital for eventual secretion of synthesized enzyme) are membrane-dependent. Negative correlations were reported between electrolyte leakages and vigor of seeds (Fatonah *et al*., 2017). The α-amylase activity on 3rd day of germinating seedlings increased gradually as seed maturation advanced from initial harvest at 9 DAA to significantly highest activity at 37 DAA. Later, after 37 DAA, the activity declined gradually until 58 DAA (Fig 4). These findings were in concurrence with the report on sorghum that the seed lots harvested at full maturity exhibited an increase in α-amylase activity during later stages of seed germination and higher vigor (Shephard *et al.*,1996; Kannababu *et al.,* 2023a; 2023b).

The seeds harvested at 37 DAA subjected to accelerated aging revealed higher storability potential, having significantly high germination, seedling growth and vigor compared to other stages of harvest. Further decrease in seed quality traits indicated that the storability could decline with seed harvest beyond 37 DAA, as evidenced by increased electrical conductivity. The superiority of physiologically matured seeds was the sum total of all the seed quality traits as reflected under stress conditions (Maria *et al.,* 2015).

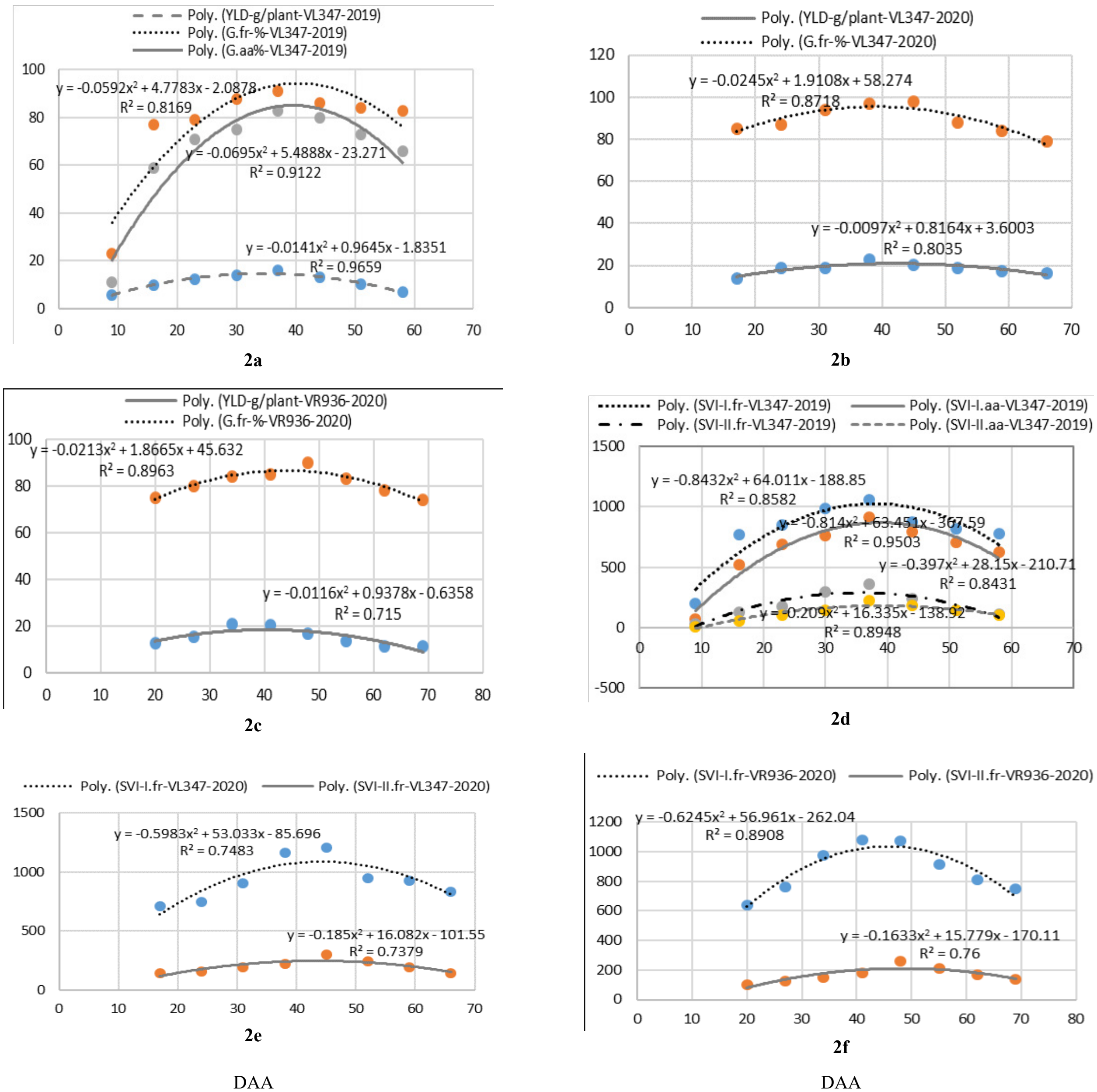

Fig 2. Polynomial regression analysis for seed yield, germination, vigour and storability traits against days after anthesis (DAA) in finger millet cultivars VL347 and VR936 during post-rainy season; Dots represent individual observations in regression analysis of different traits; **2a-b:**Yield (YLD-g/plant) and germination of fresh (fr) seeds in VL347 during 2019 and 2020 post-rainy seasons; **2c:** Seed yield (YLD-g/plant) and germination of fresh (fr) seeds in VR396 during 2020 post-rainy season; **2d:** Seedling vigour index (SVI-I and SVI-II of fresh (fr) and aged (aa) seeds in VL347 during post rainy season 2019; **2e-f:** Seedling vigour index (SVI-I and SVI-II of fresh seeds in VL347 and VR936 during post rainy season of 2020

The present results clearly differentiated the effects of seed maturation stages on seed yield, germination, seedling vigor and storability potential of finger millet cultivars (VL347 and VR936). The right stage of seed harvest is the most critical factor for seed quality and storability, as the protection mechanisms are built during the late seed maturation phase (Jalink *et al.*, 1998; 1999; Demir *et al.*, 2008). Harvesting seeds too early when there is inadequate development of essential structures and protection mechanisms may result in poor quality (Ekpong and Sukprakarn, 2008). Similarly, due to the incidence of adverse weather conditions prevailed during late harvest led to seed shattering and a decrease in seed quality (Elias and Copeland, 2001). Immature seeds with poor quality can potentially lead to poor stand establishment and a consequent decrease in the productivity of the crop. Therefore, it is essential to identify the proper stage of seed harvest for the production of high-quality seeds without loss in seed yield.

a b

Fig 3. Seed maturity (PM and HM) indices in finger millet; (a) At PM and HM stages, the plant, ears and seeds appear in brown to dark brown (copper) color; (b) At PM and HM stages, black layer depression visible prominently around the hilum of the seed.

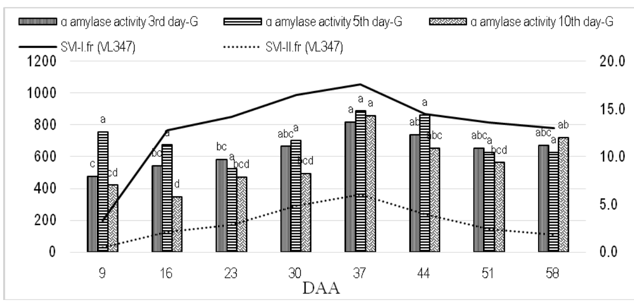

Fig 4. Effect of different stages of seed maturation on α-amylase activity (µ moles of maltose released /minute /100 seeds) at 3^{rd} , 5^{th} and 10^{th} day of seed germination (G) in finger millet cultivar VL347 during post-rainy season (PRS)

Seed development takes place soon after fertilization to maximum fresh weight accumulation in seed, and seed maturation is the end process of seed development that continues up to harvest, as differentiated by Abdul-Baki and Baker (1973). Seed development and maturation stages are determined through relative changes in seed moisture, accumulation of dry matter, desiccation tolerance, attainment of maximum seed vigor and storability at harvest maturity. Using physiological and biochemical markers, Maria *et al.* (2015) determined the physiological and harvest maturity in *Capsicum baccatum* L. seeds. Partick and Offler (2001) stated that if maximal seed vigor coincides with physiological maturity, it is likely to be the right stage of harvest. The differences in the level of 'late embryogenesis abundant (LEA) proteins' during the process of seed maturation influenced desiccation tolerance and further seed viability (Smolikova *et al*., 2020). According to Ellis (2019), the term harvest maturity is somewhat imprecise as it varies within the crop and among different crops, farming systems and locations of the world. Therefore, it is a stage of seed development when majority of seed or seed population is best suited for harvesting in high

Table 2. Effect of seed maturation stages on seed quality traits in finger millet cultivars during post rainy season (2020)

Days after anthesis (DAA)		Seed germination (%)*		Field emergence (%)*		Seedling vigour index-I		Seedling vigour index-II		Seedling dry weight (mg)		Shoot length (cm)		Root length (cm)	
VL347	VR936	VL347	VR936	VL347	VR936	VL347	VR936	VL347	VR936	VL347	VR936	VL347	VR936	VL347	VR936
17	20	85 (67.2)	75 (59.7)	83 (65.7)	73 (58.7)	710	642	145	101	1.70	1.35	3.25	3.15	5.10	5.46
24	27	87 (68.9)	80 (63.1)	86 (68.1)	79 (62.8)	746	759	157	123	1.80	1.55	3.35	3.58	5.23	5.97
31	34	94 (75.9)	84 (66.1)	93 (74.1)	83 (65.7)	903	976	191	152	2.03	1.83	4.28	4.65	5.33	7.03
37	41	97 (80.2)	85 (67.3)	96 (78.0)	84 (66.4)	1164	1078	221	181	2.28	2.13	4.50	4.80	7.50	7.88
45	48	98 (83.1)	90 (71.7)	97 (80.2)	88 (69.7)	1208	1074	299	261	3.05	2.90	4.78	4.63	7.55	7.33
52	55	88 (69.8)	83 (65.7)	87 (68.5)	82 (64.5)	951	917	244	210	2.78	2.53	4.13	3.98	6.68	7.08
59	62	84 (66.4)	78 (62.0)	83 (65.7)	77 (61.0)	929	809	195	170	2.33	2.18	4.00	3.63	7.05	6.75
66	69	79 (62.4)	74 (59.0)	77 (61.4)	73 (58.4)	836	748	145	136	1.85	1.85	3.68	3.55	6.98	6.63
CD*		*4.99*	*4.49*	*4.36*	*3.24*	*116.7*	*127*	*19.3*	*26.5*	*0.21*	*0.31*	*0.80*	*0.54*	*0.59*	*1.08*

Values in parenthesis are arcsine transformed; CD = CD ($p < 0.05$)
CD* = CD ($p < 0.05$)

seed yield combined with quality, including storability and handling traits (Black *et al.*, 2006). Physiological maturity is the end of the seed-filling period (Harrington, 1972), whereas harvest maturity is the point of time that coincides with the end of maturation drying. Black *et al*. (2006) defined harvest maturity as a stage of development at which a seed, or the majority of the seed population, is best suited to harvesting in high quality and yield, considering its storage, its handling characteristics to minimize mechanical injury, and potential field losses due to inefficient collection by harvesting equipment. In practice, harvest maturity dates vary among the crops. It may not be ideal to harvest the seeds sometimes at physiological maturity due to high moisture content due to adverse weather conditions. Therefore, a stage beyond physiological maturity, designated as harvestable maturity, seems to be the best stage for harvesting the seed crop (Tonapi *et al.*, 2006).

The indeterminate growth habit, uneven maturity, lodging and seed shattering are some of the limiting factors causing poor yield in finger millet and other millets. The maturity stage of seed crops is prone to modifications by environmental and agronomic practices (Saibabu *et al.*, 1984). The seed yield and quality traits reached to maximum level at 37 DAA, indicating that the seed attained physiological maturity at 37 DAA during the first year with VL347. Further delayed harvest at 44 DAA reduced the seed yield, vigor and storability traits significantly, indicating that the harvest maturity may fall at 40 DAA, *i.e.*, in between 37 to 44 DAA, which may be two to three days after physiological maturity. More or less similar to this, the second-year results on VL347 also confirmed these stages of physiological maturity and harvest maturity. In VR936, maximum seed quality was evident at 48 DAA. However, the difference between 41 to 48 DAA was not significant for most of the seed quality traits. Contrastingly, the seed yield traits in VR936 were highest until 41 DAA and thereafter, declined at 48 DAA. These observations provide clues on the attainment of physiological maturity at 41 DAA and possible harvest maturity two to three days later, *i.e.*, 44 DAA in VR936. The predictions using a second-order polynomial regression model for seed yield, germination, vigor and storability traits more or less closely confirmed the stages identified for physiological and harvestable maturity in finger millet cultivars. Using a polynomial regression model for seed physiological and biochemical traits, Maria *et al*. (2015), Lessa *et al*. (2017) and Kannababu *et al*. (2023a; 2023b) predicted the stages of physiological maturity and harvest maturity. The study provided useful clues that the physiological maturity generally ranges from 37 to 41 and the right stage of seed crop harvest is between 40 to 44 DAA during post rainy season in finger millet. Either early or delayed harvests under varying environmental conditions could result in considerable seed yield and quality losses.

Conclusion

The study indicated that the right stage of seed physiological maturity was at 37 DAA and possible harvestable maturity at 40 DAA in VL347. In VR936, the stage of physiological maturity reached 41 DAA and the possible harvestable maturity stage was at 44 DAA. It was predicted, in general, that physiological maturity ranges between 37 to 41 and harvestable maturity from 40 to 44 DAA in finger millet during post rainy season. However, further investigations are needed with a greater number of cultivars across seasons for the validity of these findings in general to finger millet crops. At physiological maturity and harvestable maturity stages, the plants, ears and seeds appeared in brown to dark-brown (copper) colors and the seed moisture content reduced to 13%. The black layer depression appeared around the hilum region of the seed. These symptoms are useful as morphological indices for judging the physiological maturity and identification of the right stage of crop harvest during seed production of finger millet.

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