FIELD EVALUATION OF HEAT STRESS-RESILIENT MAIZE HYBRIDS FOR IMPROVED AND STABLE MAIZE PRODUCTION IN NEPAL

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ABSTRACT

In recent years, National Maize Research Program (NMRP) aimed a paradigm shift from open-pollinated varieties (OPVs) towards hybrid maize to achieve self-sufficiency in maize for food, feed, and hybrid seed within the country. In this mission, it is necessary to identify and deploy high-yielding stress-resilient maize hybrids that can cope with climate change effects, including heat stress. Under the project “Heat Tolerant Maize for Asia (HTMA)”, NMRP introduced the hybrids that performed better in previous years in different environments from International Maize and Wheat Improvement Center (CIMMYT) Hyderabad for multi-location on-farm testing. Fifteen genotypes were evaluated at two locations, two sites in Madi, Chitwan, and one in Ghorahi, Dang, along with Rampur Hybrid-8 as a heat-tolerant check, and RML-86/RML-96 and RML-95/RML-96 as normal checks. Randomized complete block design (RCBD) was used with three replicates during the spring of 2016/17. Likewise, another 20 and 18 promising hybrids were demonstrated during the winter of 2016/17 and 2017/18, respectively, in different hybrid growing pockets considering a site — a replication. Grain yield and yield attributing traits at all locations were recorded. From the across-site data analysis, selected heat-tolerant hybrids from the experiment were CAH1432, ZH15405, ZH141592, and CAH1715 which were statistically at par with promising normal hybrid RML-86/RML-96 and superior to already released heat-tolerant Rampur Hybrid-8. In 2016/17, ZH138098, ZH1620, and VH121062 were farmers’ preferred heat-tolerant hybrids. In 2017/18, Rampur Hybrid-10, ZH141592, CAH1715, and ZH15440 were preferred by farmers. The selected best-bet are taken forward for official release/registration followed by commercialization through a public-private partnership with Nepali seed companies/cooperatives.

Keywords: Anthesis-silking interval, Heat stress, Hybrid, Resilient, Single cross

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INTRODUCTION

Maize plays a vital role in global grain production due to its high yield potential, and it is expected to become the world’s number one cereal in the future (Gong et al., 2015). It is the second cereal in terms of area (958,150 ha), production (2,893,987 t), and productivity (3.02 t ha$^{-1}$) (MoF, 2021), with the highest per capita consumption per day (98 g) among the South Asian countries (Ranum et al., 2014) in Nepal. There is a wide gap between the actual (2.84 t ha$^{-1}$) and potential yield (6.50 t ha$^{-1}$) of maize at the farmers’ level (Koirala et al., 2020a). The aggressive intervention of high-yielding climate-resilient hybrids is of the utmost importance to meet the current high demand for maize, and also to narrow down the gap between farmers’ harvest and potential yields. Hybrids and open-pollinated varieties (OPVs) occupy 12–15, and 85–88% of the total maize area in the country, respectively (Koirala et al., 2020b; 2020c). The potential yield of maize cannot be achieved only by area expansion, and popularization of OPVs, without promoting high-yielding hybrids, as stated in National Seed Vision (NSV) and Agriculture Development Strategy (ADS) (SQCC, 2013; ADS, 2015). The overall maize seed replacement rate of 17.83% (Memoire, 2017) should be reached to 33% by 2025 (SQCC, 2013). To meet the demand for hybrid maize, NSV envisaged the development and promotion of twelve and five maize hybrids by the public and private sectors, respectively, by 2025.

Driven by climate change effects, heat stress is becoming an eminent constraint of maize production in all the major maize-producing regions, including Nepal. If the current trends of global warming continue until 2050, the production and productivity of maize will be decreased by 17% in South Asia (CIMMYT, 2016). Shrestha and his colleagues (1999) predicted the warming trend after 1977 from 0.06 to 0.12°C year$^{-1}$ in most of the middle mountain and Himalayan regions of Nepal. Malla (2008) reported an average rise in temperature of 0.06°C year$^{-1}$ from 1975 to 2006. Nevertheless, the average temperature in Nepal has been increased at an annual rate of 0.06°C between 1977 and 2000, with a 0.04°C and 0.08°C increase in Terai and the Himalayas, respectively (Synnott, 2012). The expected mean annual temperatures of 1.3–3.8°C by 2060 and 1.8–5.8°C by 2090 and reduced annual precipitation of 10 to 20% can affect Nepal's agriculture sector (CIF, 2018).

The development of heat-resilient variety(ies) is an appropriate option to combat the negative impacts of climate change (Acharya and Bhatta, 2013). Heat-stress to maize is exposure to temperatures above a threshold level for a period that causes irreversible damage to growth and development, which is a function of the intensity, duration, and rate of increase in temperature (Zaidi et al., 2016). The most critical period to heat stress that is highly susceptible is from tassel emergence to early grain-filling (Vinayan et al., 2020). Spring maize, planted in the maize-rice system is estimated to be about 15.5% of the total maize in Nepal. Yield loss of spring and early summer maize reaches up to 75% due to heat-stress (Koirala et al., 2017b) causing leaf firing, silk damage, and tassel blast, which depends on the crop’s stage,
severity, and duration of stress (Monsanto, 2012). Anthesis and silking of the crop when coinciding with a temperature above 38°C leads to leaf firing and tassel blast resulting in poor pollination, and barren ears which are the critical period to determine grain yield. Lobell and Burke (2010) reported reduced higher maize yields with a 2°C rise in temperature than the reduction created by precipitation dropped more than 20%. Likewise, 13% yield reduction due to an increase in temperature by 2°C was also recorded (Rowhani et al., 2011).

However, heat stress-tolerant (HST) hybrids compared to current/normal commercial varieties could minimize yield loss by 36 and 93%, and 33 and 86% under rainfed and irrigated conditions by 2030 and 2050, respectively (Tesfaye et al., 2017). Thus, ever-increasing food/feed demand can be met only by developing climate-resilient maize hybrids. Therefore, the objectives of this study were to identify, evaluate, and deploy high-yielding HST hybrids in different agro-ecological domains of Nepal to increase maize production and productivity in the public-private partnership model.

**MATERIALS AND METHODS**

The project entitled “Heat stress-tolerant maize for Asia (HTMA)” was launched by CIMMYT and funded by the USAID under the Feed the Future (FTF) initiative using a public-private partnership approach in Nepal, India, Bangladesh, Pakistan, and the USA in 2012, and now is in the second phase. The experimental materials consisted of HST single cross hybrids selected from various trials conducted in the past. The trial set comprised fifteen single cross hybrids, including Rampur Hybrid-8, RML-86/RML-96, and RML-95/RML-96 as checks were evaluated at two sites in Madi, Chitwan; and one in Ghorahi, Dang, by using RCB with three replications during the spring of 2016/17. Likewise, NMRP conducted two demonstration sets of 20 and 18 promising hybrids along with P3533, P3535, P3396, and DKC9081 as commercial checks in different pockets of Chitwan (Madi, Rampur, and Narayanpur), Sarlahi (Sagarnath-1 and Sagarnath-2), Jhapa, Bara, and Banke districts considering a site as replication during the winter of 2016/17 and 2017/18, respectively. To shorten the longer period of 10–12 years to release a variety and to fulfill the immediate demand for hybrids of Nepali farmers, emphasis has been given to the fast-track variety release process. Therefore, multi-environment testing was emphasized rather than tested for many years. During two years period, eight locations were used including experiments and demonstrations. Madi in Chitwan and Sagarnath in sarlahi district are potential pockets for hybrids, therefore two sites in Madi for experimentation in 2016/17, and two sites for demonstration in 2016/17 and 2017/18 in Sagarnath were used. Table 1 highlights the geographical description of experimental/demonstration sites.
Table 1. Geographical description of experimental/demonstration sites at different parts of the country for the period of 2016/17 and 2017/18

<table>
<thead>
<tr>
<th>Location</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Elevation (masl)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maharanijhoda, Jhapa</td>
<td>87°42'15&quot;E</td>
<td>26°34'41&quot;N</td>
<td>103</td>
</tr>
<tr>
<td>Sagarnath, Sarlahi</td>
<td>85°40'14&quot;E</td>
<td>26°58'43&quot;N</td>
<td>130</td>
</tr>
<tr>
<td>Dumarwana, Bara</td>
<td>85°02'58&quot;E</td>
<td>27°07'41&quot;N</td>
<td>126</td>
</tr>
<tr>
<td>Narayanpur, Chitwan</td>
<td>84°23'21&quot;E</td>
<td>27°38'58&quot;N</td>
<td>198</td>
</tr>
<tr>
<td>Madi, Chitwan</td>
<td>84°21'47&quot;E</td>
<td>27°25'42&quot;N</td>
<td>253</td>
</tr>
<tr>
<td>Rampur, Chitwan</td>
<td>84°20'20.9&quot;E</td>
<td>27°39'0.3&quot;N</td>
<td>228</td>
</tr>
<tr>
<td>Ghorahi, Dang</td>
<td>82°28'38&quot;E</td>
<td>28°02'13&quot;N</td>
<td>657</td>
</tr>
<tr>
<td>Khajura, Banke</td>
<td>81°35'23&quot;E</td>
<td>28°06'48&quot;N</td>
<td>181</td>
</tr>
</tbody>
</table>

The plot size of an individual entry in the experiment was 12m$^2$, consisting of four rows of 5-m long, whereas the plot size was 30m$^2$, which is ten rows of 5-m long in demonstration sets. The row-to-row and plant-to-plant distances were 60 and 25 cm, respectively, both in experiments and demonstrations. Farmyard manure (FYM) $\times 15$ t ha$^{-1}$ in combination with chemical fertilizer $\times 180:60:40$ N:P$_2$O$_5$:K$_2$O kg ha$^{-1}$ was applied. CIMMYT's procedures (CIMMYT, 1985) were adopted to measure days to 50% anthesis and silking, plant and ear heights, field weight, and other parameters as given below:

**Days to 50% anthesis:** The number of days from planting until the date which 50% of the plants in a plot are shedding pollen.

**Days to 50% silking:** The number of days from planting until 50% of the plants in a plot has silks 2-3 cm long.

**Anthesis-silking interval (ASI):** This is the interval in days between days to 50% silking and days to 50% anthesis.

**Plant height:** The distance in cm from the plant base to the point where the tassel starts to branch. Measurement is taken from five randomly selected plants.

**Ear height:** The distance from the plant base to the node bearing the uppermost ear in cm. For convenience, the same five plants whose plant height was measured are used to measure this trait.

**Ear position:** Ear height divided by plant height showing the point of ear placement in the plant.

**Field weight:** Weight of the ears harvested from central rows in kilograms to one decimal place.
**Moisture content (%)**: Ten ears are selected from each plot, two central kernel rows on each one is removed, grains are mixed, and with this sample, moisture percentage is determined in the grain at harvest. We have to delay the harvest of maize until its moisture content is low (15-25%). Doing so, the grain is much easier to shell for moisture content determination and most moisture meters are more accurate at low moisture levels.

**Grain yield**: Field weight was converted into grain yield (t ha\(^{-1}\)) by adjusting 80% shelling recovery and 15% moisture level using the following formula adopted by Koirala et al. (2017c).

\[
\text{Grain yield (kg/ha)} = \frac{\text{F.W. (kg plot}^{-1}\text{)} \times (100-\text{M.C.}) \times \text{SP} \times 10,000}{85 \times \text{Net harvested area (m}^2\text{)}}
\]

Where,

- F.W. = Fresh weight of harvested ears in kg per plot
- M.C. = Grain moisture content in percent at harvest
- SP = Shelling percent
- 85 = Grain moisture adjusted to 15%

Except for grain yield, mean values combined over locations/sites have been presented in the tables.

**Statistical analysis**: The data were recorded and analyzed using ADEL-R software. The significant differences between genotypes were calculated using the least significant difference (LSD) test at 1% or 5% level of significance, respectively (Gomez and Gomez, 1984).

**RESULTS AND DISCUSSION**

**Experiment**

There was a difference among the genotypes for days to 50% anthesis at Ghorahi, Dang, during spring 2016/17. Three hybrids, such as ZH15405, ZH15272, and Rampur Hybrid-8 flowered three days earlier than average days to flowering of 62 days, whereas genotypes RML-95/RML-96 and ZH1615 flowered 5–6 days later. Genotypes varied for the average plant and ear height. Plant height ranged from 151 cm of CAH1432 to 195 cm of CAH1715, whereas ear height ranged from 53 cm of ZH1615 to 85 cm of ZH1611. The ear position of the tested hybrids ranged from 0.33 of ZH1615 to 0.48 of ZH1611 when combined over locations. The grain yield of the tested hybrids at individual locations did not differ significantly (P>0.05), however, significant differences among the genotypes were recorded when data were averaged over locations (P<0.05). The mean grain yield ranged from 4.3 to 6.45 t ha\(^{-1}\) (Table 2).
Table 2. Grain yield and other traits of heat stress-tolerant hybrids tested at various sites (Madi-1, Madi-2, and Ghorahi) of Terai, 2016/17 spring

<table>
<thead>
<tr>
<th>Genotype</th>
<th>AD+</th>
<th>PH</th>
<th>EH</th>
<th>EP</th>
<th>Grain yield, t ha(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Madi-1</td>
</tr>
<tr>
<td>CAH1432</td>
<td>64</td>
<td>151</td>
<td>61</td>
<td>0.40</td>
<td>6.81</td>
</tr>
<tr>
<td>ZH15405</td>
<td>62</td>
<td>153</td>
<td>61</td>
<td>0.40</td>
<td>7.07</td>
</tr>
<tr>
<td>ZH141592</td>
<td>63</td>
<td>162</td>
<td>61</td>
<td>0.37</td>
<td>5.73</td>
</tr>
<tr>
<td>RML-86/RML-96</td>
<td>66</td>
<td>169</td>
<td>69</td>
<td>0.41</td>
<td>7.24</td>
</tr>
<tr>
<td>CAH1715</td>
<td>65</td>
<td>195</td>
<td>78</td>
<td>0.40</td>
<td>6.64</td>
</tr>
<tr>
<td>Rampur Hybrid-8</td>
<td>62</td>
<td>191</td>
<td>81</td>
<td>0.43</td>
<td>6.17</td>
</tr>
<tr>
<td>ZH1611</td>
<td>63</td>
<td>176</td>
<td>85</td>
<td>0.48</td>
<td>6.12</td>
</tr>
<tr>
<td>CAH175</td>
<td>68</td>
<td>177</td>
<td>71</td>
<td>0.40</td>
<td>6.12</td>
</tr>
<tr>
<td>CAH1418</td>
<td>68</td>
<td>164</td>
<td>69</td>
<td>0.42</td>
<td>5.99</td>
</tr>
<tr>
<td>ZH1615</td>
<td>71</td>
<td>160</td>
<td>53</td>
<td>0.33</td>
<td>7.30</td>
</tr>
<tr>
<td>CAH1727</td>
<td>66</td>
<td>181</td>
<td>73</td>
<td>0.40</td>
<td>5.80</td>
</tr>
<tr>
<td>ZH15272</td>
<td>62</td>
<td>157</td>
<td>64</td>
<td>0.41</td>
<td>5.65</td>
</tr>
<tr>
<td>VH123050</td>
<td>67</td>
<td>167</td>
<td>61</td>
<td>0.37</td>
<td>5.22</td>
</tr>
<tr>
<td>ZH15383</td>
<td>63</td>
<td>169</td>
<td>75</td>
<td>0.44</td>
<td>5.17</td>
</tr>
<tr>
<td>RML-95/RML-96</td>
<td>70</td>
<td>167</td>
<td>77</td>
<td>0.46</td>
<td>4.50</td>
</tr>
<tr>
<td>Minimum</td>
<td>62</td>
<td>151</td>
<td>53</td>
<td>0.33</td>
<td>4.50</td>
</tr>
<tr>
<td>Maximum</td>
<td>71</td>
<td>195</td>
<td>85</td>
<td>0.48</td>
<td>7.30</td>
</tr>
<tr>
<td>Mean</td>
<td>65</td>
<td>170</td>
<td>70</td>
<td>0.41</td>
<td>6.10</td>
</tr>
</tbody>
</table>

F-test                  ns  ** ns  ns  ns  *  
\(\text{LSD}_{0.05}\)    5.6  16.85 10.70 -   -   -   1.51 
\(\text{CV}, \%\)         4    5.94  9.20 14.46 12.92 26.8 16.0

AD+: Days to 50% anthesis (data recorded only from Ghorahi), PH: Plant height in cm, EH: Ear height in cm, and EP: Ear position (data recorded from Madi-1, Madi-2, and Ghorahi)

**Demonstration**

In 2016/17, genotypes differed for days to 50% anthesis (\(P<0.001\)), days to 50% silking (\(P<0.001\)), plant height (\(p<0.001\)), and ear height (\(P<0.001\)) when combined over locations (Rampur, Sagarnath-2, Sagarnath-2, Narayanpur and, Madi) (Table 3). Days to 50% anthesis ranged from 94 (ZH1521) to 112 days (ZH1615) when averaged across locations. A similar trend was observed for days to 50% silking that ranged from 97 (ZH1521) to 116 days (ZH1615). Anthesis-silking interval (ASI) ranged from two to four days among the hybrids. Hybrids with shorter mean plant
and ear height of 186 and 88 cm and extended plant and ear height of 223 and 115 cm, respectively, were observed at NMRP Rampur and Sagarnath-1 (data not shown). Mean plant height among the hybrids ranged from 166 cm for CAH1432 and VH112337 to 257 cm for P3535 with a demonstration mean value of 202 cm. The ear height ranged from 65 cm (VH112337) to 128 cm (P3535). Ear position was ranged from 0.39 for VH112337 to 0.57 for Rampur Hybrid-6 (Table 3).

Table 3. Combined quantitative traits of heat stress-resilient hybrids demonstrated at various sites (Rampur, Sagarnath-1, Sagarnath-2, Narayanpur, and Madi) in Terai condition, 2016/17 winter

<table>
<thead>
<tr>
<th>Genotype</th>
<th>AD</th>
<th>SD</th>
<th>ASI</th>
<th>PH</th>
<th>EH</th>
<th>EP</th>
</tr>
</thead>
<tbody>
<tr>
<td>VH112337</td>
<td>107</td>
<td>110</td>
<td>3</td>
<td>166</td>
<td>65</td>
<td>0.39</td>
</tr>
<tr>
<td>ZH141592</td>
<td>107</td>
<td>109</td>
<td>2</td>
<td>196</td>
<td>95</td>
<td>0.48</td>
</tr>
<tr>
<td>ZH1521</td>
<td>94</td>
<td>97</td>
<td>3</td>
<td>193</td>
<td>94</td>
<td>0.49</td>
</tr>
<tr>
<td>CAH178</td>
<td>107</td>
<td>109</td>
<td>2</td>
<td>183</td>
<td>88</td>
<td>0.48</td>
</tr>
<tr>
<td>ZH138038</td>
<td>102</td>
<td>105</td>
<td>3</td>
<td>172</td>
<td>91</td>
<td>0.53</td>
</tr>
<tr>
<td>Rampur Hybrid-10</td>
<td>107</td>
<td>109</td>
<td>2</td>
<td>203</td>
<td>102</td>
<td>0.50</td>
</tr>
<tr>
<td>CAH1715</td>
<td>111</td>
<td>114</td>
<td>3</td>
<td>236</td>
<td>120</td>
<td>0.51</td>
</tr>
<tr>
<td>CAH177</td>
<td>98</td>
<td>101</td>
<td>3</td>
<td>211</td>
<td>114</td>
<td>0.54</td>
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<tr>
<td>CAH153</td>
<td>111</td>
<td>115</td>
<td>4</td>
<td>215</td>
<td>113</td>
<td>0.53</td>
</tr>
<tr>
<td>CAH1719</td>
<td>108</td>
<td>110</td>
<td>2</td>
<td>208</td>
<td>94</td>
<td>0.45</td>
</tr>
<tr>
<td>CAH175</td>
<td>98</td>
<td>102</td>
<td>4</td>
<td>200</td>
<td>101</td>
<td>0.51</td>
</tr>
<tr>
<td>Rampur Hybrid-8</td>
<td>111</td>
<td>113</td>
<td>2</td>
<td>21</td>
<td>110</td>
<td>0.51</td>
</tr>
<tr>
<td>ZH1505</td>
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<td>110</td>
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<td>202</td>
<td>103</td>
<td>0.51</td>
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<tr>
<td>CAH1432</td>
<td>98</td>
<td>102</td>
<td>4</td>
<td>166</td>
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<td>ZH1611</td>
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<td>ZH1615</td>
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<td>116</td>
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<td>203</td>
<td>99</td>
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<td>P3533</td>
<td>108</td>
<td>111</td>
<td>3</td>
<td>227</td>
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<td>0.54</td>
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<td>P3535</td>
<td>107</td>
<td>110</td>
<td>3</td>
<td>257</td>
<td>128</td>
<td>0.50</td>
</tr>
<tr>
<td>Rampur Hybrid-4</td>
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<td>114</td>
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<td>175</td>
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<td>Rampur Hybrid-6</td>
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<td>113</td>
<td>4</td>
<td>182</td>
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<tr>
<td>Minimum</td>
<td>94</td>
<td>97</td>
<td>2</td>
<td>166</td>
<td>65</td>
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<tr>
<td>Maximum</td>
<td>112</td>
<td>116</td>
<td>4</td>
<td>257</td>
<td>128</td>
<td>0.57</td>
</tr>
<tr>
<td>Mean</td>
<td>106</td>
<td>109</td>
<td>3</td>
<td>202</td>
<td>102</td>
<td>0.50</td>
</tr>
<tr>
<td>F-test</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LSD0.05</td>
<td>1.7</td>
<td>1.9</td>
<td>21.1</td>
<td>13.7</td>
<td></td>
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</tr>
<tr>
<td>CV, %</td>
<td>1.3</td>
<td>1.4</td>
<td>8.3</td>
<td>10.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

AD: Days to 50% anthesis, SD: Days to 50% silking, ASI: Anthesis-silking interval, PH: Plant height in cm, EH: Ear height in cm, EP: Ear position
The mean grain yield differed during the winter of 2016/17 significantly (P<0.05) among the hybrids when combined over locations. The mean grain yield was 6.69 t ha\(^{-1}\). The grain yield among the locations varied from 3.88 t ha\(^{-1}\) (Narayanpur site; P>0.05) to 6.82 t ha\(^{-1}\) in Madi (P>0.05). The highest mean grain yield of 10.11 t ha\(^{-1}\) was recorded at Sagarnath-1 (P>0.05) (Table 4).

Table 4. Grain yield (t ha\(^{-1}\)) of heat stress-tolerant maize hybrids demonstrated at various locations (Rampur, Sagarnath-1, Sagarnath-2, Narayanpur, and Madi) in Terai, 2016/17 winter

<table>
<thead>
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The hybrids set for demonstration purposes also differed for days to 50% anthesis (P<0.05), days to 50% silking (P<0.05), and plant height (P<0.05) across Terai when...
data combined over locations in winter 2017/18. The days to 50% anthesis varied from 112 days of ZH15286 and ZH138077 to 126 days of CAH1723 with a mean of 118 days. The days to 50% silking ranged from 115 to 129 days with a mean value of 121 days. The minimum plant height of 179 cm was measured for ZH1718, whereas the maximum plant height of 211 cm was attained by DKC9081 with a mean value of 194 cm when combined over locations (Table 5).

Table 5. Combined quantitative traits of heat stress-resilient maize hybrids demonstrated at various Terai locations (Maharanijhoda, Sagarnath-1, Sagarnath-2, Dumarwana, Madi, Rampur, and Nepalgunj), 2017/18 winter

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<th>PH</th>
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AD: Days to 50% anthesis, SD: Days to 50% silking, ASI: Anthesis-silking interval, PH: Plant height in cm, EH: Ear height in cm, EP: Ear position
The mean grain yield during 2017/18 varied (p<0.05) among genotypes when combined over locations. The mean grain yield was 8.57 t ha⁻¹ where DKC9081 had yielded the highest (11.16 t ha⁻¹). Hybrids produced a higher grain yield of 10.72 t ha⁻¹ at Khajura, followed by 10.59 t ha⁻¹ at Sagarnath-1 and 9.07 t ha⁻¹ at Sagarnath-2. HSR hybrids such as Rampur Hybrid-10 (9.52 t ha⁻¹), ZH141592 (9.24 t ha⁻¹), CAH1715 (8.83 t ha⁻¹), and ZH15440 (8.77 t ha⁻¹) were statistically similar (p>0.05) to P3396 (10.22 t ha⁻¹) (Table 6).

Table 6. Grain yield (t ha⁻¹) of heat stress-tolerant hybrids demonstrated at various locations in the Terai environment, 2017/18 winter

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MJ: Maharanijhoda, Jhapa; SS¹: Sagarnath, Sarlahi, location 1; SS²: Sagarnath, Sarlahi, location 2; DB: Dumarwana, Bara; MC: Madi, Chitwan; RC: Rampur, Chitwan; NB: Nepalgunj, Banke
Prasanna in 2018 reported that 80% of the total maize area in South and South East Asia is rainfed which is prone to various climatic extremes such as drought, heat, waterlogging, acidity, or a combination of drought and heat. Abiotic stress-tolerant varieties are beneficial in the context of climate change in minimizing the production risks and improving farmers’ livelihoods (Raghu et al., 2015). Grain yield may reduce by 101 kg ha⁻¹ on a daily basis if a temperature of 35°C remains during pollination and grain filling stages (Naveed et al., 2016). All aspects of maize plants are affected by heat stress. It decreases plant height by 15% (Traore et al., 2000) producing short internodes (Weaich et al., 1996), reduces life cycle, retards growth and development (Chaubey et al., 2016), inhibits kernel growth rate, weight (Commuri and Jones, 2001) resulting in reduced grain yield.

HST hybrids can play a game-changer role to increase production and productivity in the context of climate change for sustainable food and feed security. High night-time temperatures affected maize yields in 2010 and 2012 across the U.S. Corn Belt (EPA, 2016). As climate change is a global phenomenon, Wang et al. (2011) predicted with >90% probability that a 15% maize yield reduction in the Jilin province of China may occur in 2070 due to the combined effect of temperature and precipitation changes. Due to more than a 5°C temperature increase in Iowa by the end of the 21st century, maize yield is estimated to decrease by 18% (Ummenhofer et al., 2015). Likewise, 15 to 50% maize yield reduction is predicted from the late 20th century to the middle and late 21st century in Iowa (Xu et al., 2016). In the case of Africa and Latin America, a 10% yield reduction has been predicted (Seed Map) to 2055 (Jones and Thornton, 2003). It is estimated that the average temperature in Nepal increased at an annual rate of 0.06°C from 1977 to 2000. The increment was 0.04°C in Terai and 0.08°C in the Himalayas (Synnott, 2012). Scientists in Zimbabwe also identified heat and drought stress-resilient maize hybrids and named them game-changer technology (ANGOP, 2016).

The tasseling, silking, pollination, and grain filling are extremely critical stages to have increased maize yields. Days to 50% anthesis and silking play a crucial role in identifying the maturity period and anthesis to the silking interval of the cultivar. Top yielding genotypes, such as P3396, Rampur Hybrid-10, CAH1715, ZH141592, CAH178, and CAH1719 have a lower ASI value. These hybrids have better synchrony between male and female flowers (Table 3 and 6) indicating better pollination even in the stress environment. This finding is in line with the findings of Noor et al. (2019). Edmeades et al. (2017) also showed a high positive correlation of grain yield with ASI in drought conditions. Similarly, Deutsch and his colleagues (2018) predicted 10–25% yield losses of major cereals – rice, maize, and wheat due to a per degree increase of global mean surface warming.

Plant and ear heights are considered important traits not only for higher grain yield but also for lodging resistance, disease reactions, fodder value, and tackling niche-specific farmers’ problems. In demonstrations, the ear position of 50% and 83% of the hybrids in 2016/17 and 2017/18 was ≤0.50 and were tolerant of lodging.
In the experiment conducted during the spring of 2016/17, CAH1432, ZH15405, ZH141592, and CAH1715 heat-tolerant hybrids produced up to 14% higher grain yield than heat-tolerant registered Rampur Hybrid-8 (Table 2). CAH178, CAH1719, and CAH1432 produced grain yield statistically at par with P3533 and P3535 in the demonstration during the winter of 2016/17 (Table 4). Similarly, ZH141592 and Rampur Hybrid-10 were statistically at par with commercial check P3396 during the winter of 2017/18 (Table 6). The findings of these experiments agreed with the findings of Setimela (2017) who reported that climate-resilient hybrids had produced 20–25% higher grain yield compared to commercial varieties under low-input and stress environments in eastern and southern Africa. Likewise, other HTMA hybrids such as ZH191085 and ZH182082 tested by the Indian Institute of Maize Research (ICAR, 2020) yielded more than 8 t ha⁻¹ under heat stress conditions. Generally, farmers harvest 6–7 t ha⁻¹ grain yield from multi-national company hybrids. Therefore, the nationally developed and identified heat stress-resilient hybrids producing grain yield more than 7 t ha⁻¹ in demonstrations are potential hybrids for the future.

CIMMYT first licensed the heat-stress resilient maize hybrids for deployment in Nepal in 2015 (CIMMYT, 2015). The HST hybrids identified better and licensed to Nepal are CAH1513, CAH1520, CAH158, CAH1511, and CAH1515 in 2015, CAH151, and CAH153 in 2016, and CAH1715 and CAH1721 in 2017. The first two HST hybrids, registered in Nepal were CAH151 and CAH153, as Rampur Hybrid-8 and Rampur Hybrid-10 for commercial cultivation in Terai and inner Terai regions up to 700 masl (Koirala, 2017a). For the first time in Nepal, the F1 seed of HST maize hybrids was produced on a larger scale in isolation by Lumbini Seed Company Pvt. Ltd., Rupandehi and Namuna Ekikrit Sahakari Kheti, Maharanijhoda, Jhapa in close collaboration with NMRP and had produced the seed yield of 2.5 and 2.2 t, respectively, in 2018/19 winter. As reported by hybrid growing farmers, the yield performance of Rampur Hybrid-10 is at par with better multi-national company hybrids, and its demand is in an increasing trend. In 2019/20 winter, Namuna Ekikrit Sahakari Kheti, Maharanijhoda, Jhapa; Madan Bhandari Memorial Academy, Morang; Lumbini Seed Company Pvt. Ltd., Rupandehi; Gorkha Seed Company Pvt. Ltd., Dang; Unique Seed Company Pvt. Ltd., Dhangadhi, Kailali, and Panchashakti Seed Company Pvt. Ltd., Dhangadhi, Kailali were engaged in producing 30.5 t F1 seed of Rampur Hybrid-10 as well as maintaining their parental lines in close collaboration with NMRP Rampur. Koirala et al. (2021) conducted various experiments on hybrid maize during winter from 2016/17 to 2018/19 in Terai and inner Terai ecological belt across Nepal and identified CAH1715, RML-86/RML-96 and, RML-95/RML-96 promising like in experiments and demonstrations as mentioned in this paper. Therefore, these hybrids are in the pipeline for release/registration, which will provide hybrids' selection options to both growers and seed producers. Neupane et al. (2020) reported that in addition to Rampur Hybrid-10,
pipeline hybrids RML-86/RML-96 and RML-95/RML-96 are also heat stress-tolerant among the NMRP developed hybrids. Therefore, it is the right time to shift from OPVs to hybrids with remarkable emphasis on stress-resilient ones.

Increasing demand for maize, both for food and feed should come from increased yield in maize-based cropping system as an expansion of maize area forever is almost impossible. To develop self-reliance in maize; it is high time to adopt hybrid maize technology in Terai, inner Terai, foothill valleys, and potential pockets of the middle hills of Nepal, urgently and aggressively. If hybrids are the only potential options, it is always better to move with stress-resilient hybrids targeting climate change adaptation strategy (Cairns and Prasanna, 2018), and increased production and productivity as well, to translate the goal of maize self-sufficiency into reality. For this, 25% of the total maize area should be covered by native hybrids with an average yield of ≥6.00 t ha−1 in the farmers’ fields that will boost the average national maize productivity of 4.00 t ha−1. Efficient, profitable, and sustainable seed production should be done by private entrepreneurs in the public-private partnership model. To maintain this yield level, the contribution of hybrids and OPVs to total maize SRR should reach 25 and 8%, respectively. For this, there should be strong support from the government, and Nepal Agricultural Research Council (NARC) to "Hybrid maize factory" NMRP regarding well-equipped human, infrastructure, and financial resources to move hybrid research programs as per present and future demand of the country.

**CONCLUSION**

Developing and deploying heat stress-resilient (HSR) hybrids instead of OPVs could make the country self-sufficient for food, feed, and seed. The selected HSR hybrids are with ASI less than three, ear position at around the center point of the stalk, and produced grain yield more or at par with popular prevailing multi-national hybrids. The performances of hybrids such as CAH1432, ZH15405, ZH141592, CAH1715, CAH178, CAH1719, and CAH1432 need to be re-verified and released/registered for commercial cultivation. Then, these hybrids should be deployed in a public-private partnership model to generate employment opportunities and food/feed security for Nepal. Generally, heat and drought stresses appear together in rainfed agriculture in Nepal and therefore should be tackled together in the future in the case of maize.

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