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Impact of freezing temperatures on winter maize production in the Yaqui Valley, Sonora, Mexico

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Abstract

The objective of this work was to measure the physical damage and impact on production caused by freezing temperatures that occurred in January 2023 on the maize crop in the Yaqui Valley, Sonora, Mexico. Field trips were carried out to monitor the damage in 134 commercial fields which represented 5,256 hectares. The damage estimate was accounted for by visual inspection, calculating the percentage of green area affected by the freezing temperatures multiplied by the population damaged; also, the percentage of foliar damage and the sowing date were correlated with grain yield. Eighteen fields sown with different maize hybrids on different dates, and with different percentage of damage, were selected to evaluate the weather effect, by harvesting six random samples 1 m^2. The number of ears per plant were counted considering the complete and incomplete ones, and the grain weight was standardized to 12 % humidity. The estimated average foliar damage in the total area monitored was 30.24 %. The lowest damage was related to the irrigation applied before the freezing temperatures occurred, while the greatest damage in fields sown early, was related to the phenological stages 9th to the 11th ligulated leaves. The interaction between foliar damage and grain yield indicated that for every 1 % damage, yield was reduced by 0.0228 t ha^{-1} and the average production of the fields by 1.85 t ha^{-1}, while for late sowing, grain yield was reduced by 0.0638 t ha^{-1} per day of delay, and the average production of the fields by 1.53 t ha^{-1}.

Key words: Maize; *Zea mays*; Freezing Temperature; Foliar Damage; Grain Yield

1. Introduction

Maize (*Zea mays* L.) is the most important agricultural crop in Mexico from the food, industrial, political, and social point of view [1]. In the southern part of the state of Sonora, the cultivation of maize actively contributes to the regional economy and is relevant for the crop pattern of the fall-winter season, occupying second place in importance in terms of sowing area, only after wheat; but the current production system requires changes or adjustments that would contribute to mitigate the effects of climate change, and to adapt to current needs to ensure the integrity and profitability of the crop [2]. In southern Sonora, maize cultivation has been technologically recommended in various sowing dates: for spring from March 1 to 31, for the summer during the second fortnight of August [3]; Ortega *et al*. [4] also recommend sowing during June. For the fall-winter season, Cota Agramont *et al*. [5] recommend sowing from the second week of August to September 10 in order to evade frost damage, and sowing of sweet maize for canning from October to

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February. More recently, Valenzuela Borbón *et al*. [6] recommend sowing maize in December, since yield potential is high and with a low risk of frost damage for the current hybrids used in the region; they have also reported that sowing in October-November, hybrids show the highest grain yield, but the risk of frost is greater. Southern Sonora has experienced climatic abnormal temperature events, like the frosts during the 2003-2004 and 2010-2011 crop seasons [7], where even the wheat producers were affected by the magnitude of the damage, and for the limitations of the crop insurance coverage, and an unusually warm and humid one during 2014-2015, which caused losses in several crops [8,9]. Maize has been affected by low temperatures with damage ranging from low to total loss [6] in four of the last eight crop seasons. Temperature is the most important factor that influences the development of the maize plant through its phases, from emergence to flowering and maturity [10]. A frost occurs when the temperature on the surface of the soil and on objects located on it, is equal to or lower than the freezing point of water [11]. In addition to the damage caused by a frost, there are others caused by cooling with temperatures between 0 and 10 °C, which do not cause the immediate death of the plant, but rather a physiological imbalance that affects yield [12]. There are different methods to reduce the effects of frosts on crops, one of the oldest methods is the use of water to counteract the frost, or producing artificial fog or smoke [13]. The severity of a frost damage will depend largely on the duration and extent of low temperatures, also considering the susceptibility of the maize plant tissue and organs. Leaves are more susceptible because their thinness makes it difficult for them to maintain heat, the stems and grain which are the thickest tissues of the plant, have a greater heat retention capacity [14]. Damage caused by temperatures between 0.5 and 7 °C manifests itself as a decrease in the color of the plant, they acquire shades that resemble gray-green, purple and mottled red with increased yellowish color, and a slowdown in photosynthesis [15]. According to Sevilla [16] and Schmidt [17], the accumulation of persistent cold at temperatures below 5 °C has been associated with grain yield reduction in maize [16]. Cold or low temperature stress has many negative effects on the maize plant, some of which are a marked reduction in aerial biomass, dwarfism, prolongation of the vegetative period and decrease or inhibition of grain production per ear [17]. A season of good performance is associated with a comfortable climatic condition, and the opposite, as it has happened in seasons of low performance, with an accumulation of minimum or maximum temperatures that generate physiological stress. The objective of this work was to measure the physical damage and the impact on maize production exerted by the freezing temperatures that occurred in January 2023 in some commercial maize fields in the Yaqui Valley, Sonora, Mexico.

2. Materials and methods

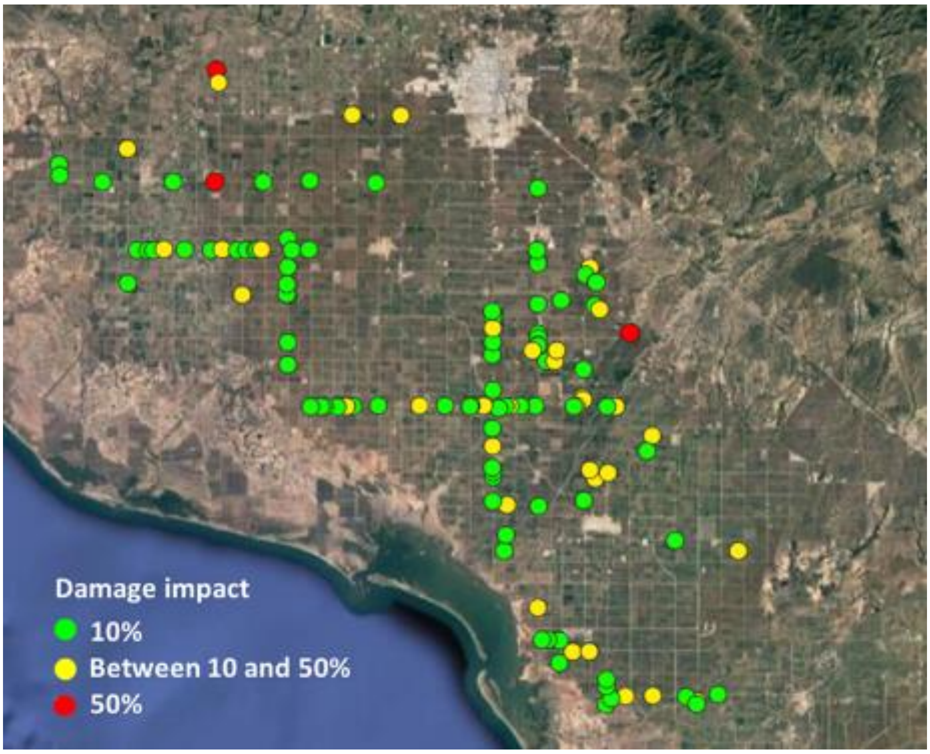

Figure 1 Commercial maize fields monitored for damage by freezing temperatures in the Yaqui Valley, Sonora, Mexico, in January 2023.

The temperature data for the month of January 2023 was downloaded in an hourly format from the automated weather station network in the state of Sonora (REMAS) [18], which comprised 21 stations in the agricultural area of the Yaqui Valley in the same state. Temperature lower than and equal to 4 °C in each weather station was filtered, in order to determine the areas exposed to the freezing temperatures and that could be damaged. Based on this information, field trips were carried out to monitor commercial maize fields that were exposed to those temperatures. The monitoring covered a total of 13 transects (Figure 1), which included 134 fields with a total area of 5,256 hectares. The average number and accumulation of cold units (CU) from each meteorological station was calculated, considering a CU as one hour recorded with a temperature below 10 °C [19]. The estimate of the effect of the freezing temperatures was determined by visual inspection, and multiplying the percentage of the green area affected by the population damaged. Subsequently, 18 fields with different percentages of damage and on different planting dates and maize hybrids were selected (Table 1, Figure 2) [20,21,22]). From each field, six 1 m^2 random samples were extracted, and the number of complete and incomplete ears were counted, and the grain weight (12 % humidity) was recorded. Through regression, grain yield was correlated with percentage of foliar damage and with sowing date.

Table 1 Commercial maize fields evaluated for freezing damage in the Yaqui Valley, in January 2023.

Block	Sowing date	Hybrid	Damage by freezing temperatures (%)	Grain yield (t ha^{-1})
1414	14/11/2022	Hipopótamo	46.8	14.53
1123	14/11/2022	Hipopótamo	0.8	21.18
1710	20/11/2022	DK-4050	32	17.73
2018	20/11/2022	Hipopótamo	36	12.03
1213	20/11/2022	Hipopótamo	14	15.02
115	25/11/2022	Hipopótamo	1	16.25
1608	01/12/2022	Hipopótamo	42	12.66
1414 L*	01/12/2022	Hipopótamo	25	11.58
703	02/12/2022	DK-5021	4	17.29
407	05/12/2022	DK-4050	38	14.36
2324	05/12/2022	Hipopótamo	20	10.36
629	06/12/2022	Hipopótamo	6	15.36
617	10/12/2022	Hipopótamo	76.5	12.96
1824	13/12/2022	Hipopótamo	48.8	13.91
1318	13/12/2022	Hipopótamo	81	12.97
1216	22/12/2022	Hipopótamo	14	12.66
117	30/12/2022	Hipopótamo	76.5	15.42
2914	06/01/2023	DK-4050	0	13.16

L* = late sowing in the same block.

Figure 2 Location of 18 maize commercial fields selected for monitoring and sampling in the Yaqui Valley, Sonora.

3. Results and discussion

During the month of January, the temperature in the Yaqui Valley ranged between 2.75 °C and 28.52 °C with an average of 14.05 °C (Figure 3). The accumulated CU recorded on average were 245. The weather stations with the highest number of CU were Corral Station, Block 1418, and Block 1730 with 297, 295, and 291 CU, respectively, and those with the lowest number of CU were Block 419 and 1423 with 184 and 188.

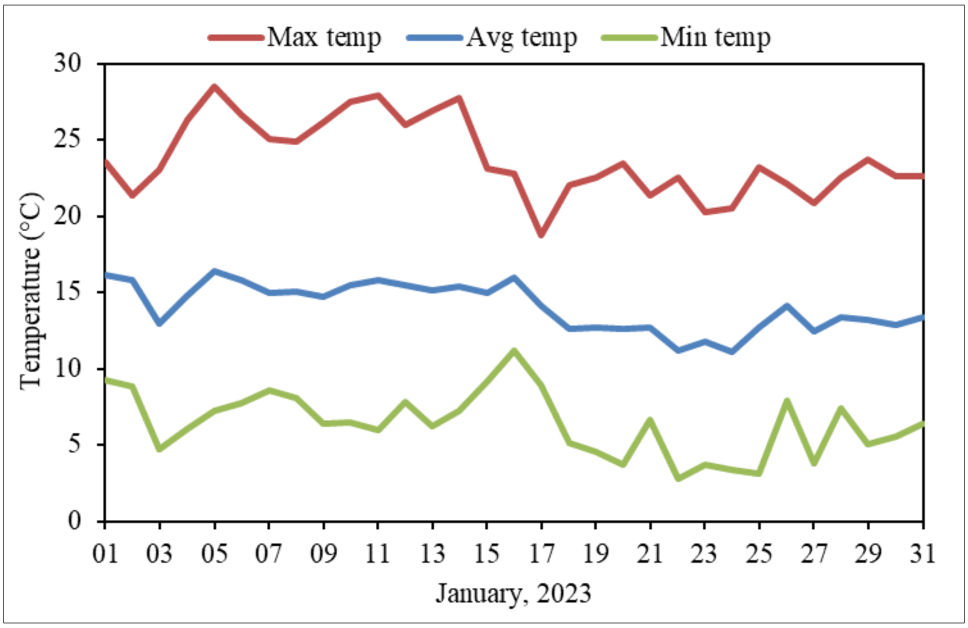

Figure 3 Maximum, minimum and average temperature recorded from 21 weather stations in January 2023, in the Yaqui Valley, Sonora, Mexico.

The minimum temperatures lower than and equal to 4 °C from all the weather stations occurred on January 3, 4, 13, and there was an overall increase in the number of hours from January 18 to 29, with a maximum of 75 hours on January 22 and a minimum of 6 on January 21 (Figure 4). The highest number of hours of this thermal level occurred from January 22 to 25 with a range of 58 to 75 and average of 67.7. A total of 428 hours accumulated during January from all the weather stations, being the central-eastern zone of the agricultural territory the coldest zone in the month. This event of freezing temperatures occurred on three commercial hybrids in a region, the Yaqui Valley, which is basically at the sea level; however, there are maize hybrids tolerant to high frequency of cold conditions at 3,350 masl in other parts of the world [23]. Freezing temperatures prior to plant maturity can cause grain yield losses, although severity might greatly vary based on local climate conditions, crop maturity, and topographical features [24]. A maize killing freeze occurs when temperatures reach 0 °C for four hours or -2.2 °C for minutes. In plants subjected to very low temperatures below -4 °C, ice crystals form in the intracellular spaces of the exposed tissues, causing the death of the cells and the plant in general. It is the formation of these ice crystals in the intercellular spaces and not the low temperature per se that causes great damage to the aerial biomass and death of the plant [25]. Ice crystals form from water that is slowly exuded from the cytoplasm during the freezing process. Even if ice crystals do not form, leaf tissue can exhibit irreversible damage, which is the result of dehydration induced by extreme cold. Low temperatures significantly affect the vegetative period of the plant [26]. Although the maize plant is not damaged, the prolongation of its life cycle caused by low temperatures has great agronomic and economic importance, the cost of cultivation increases, as well as the risk that its yield will decrease due to attacks by pathogens and early frosts. A killing freeze can still happen with temperatures above 0 °C, in low and unprotected areas when there's no wind maize leaves are more easily damaged than stalks, and leaves above the ears are more susceptible to injury than those below.

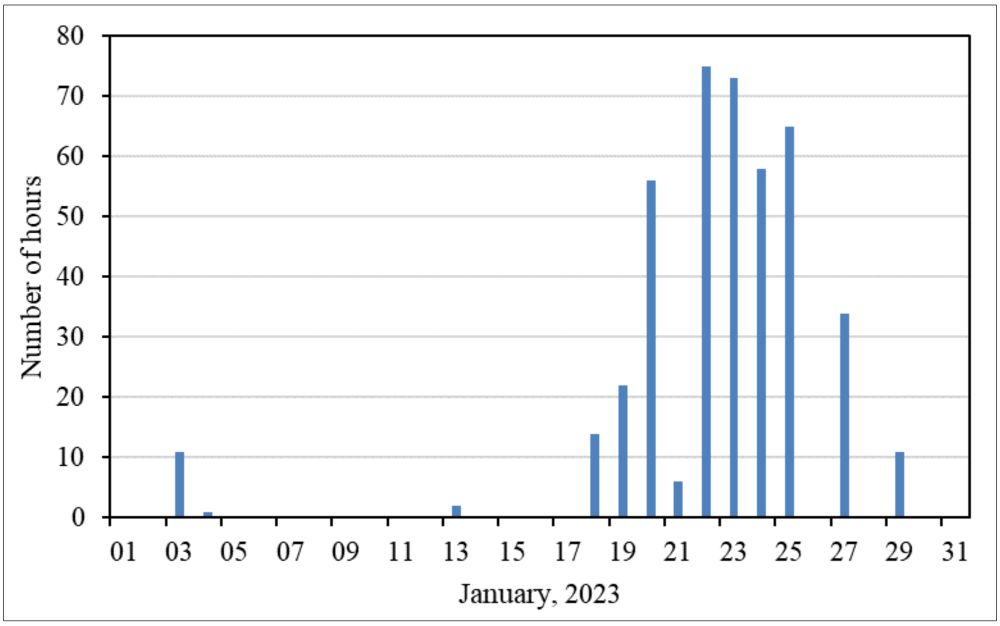

Figure 4 Daily accumulation of hours ≤ 4 °C, recorded from 21 weather stations in January 2023, in the Yaqui Valley, Sonora, Mexico.

Freeze-damaged leaves initially appear as water-soaked, they are light green to gray after drying and later turn brown (Figure 5). Bremer *et al.* [15] reported that the damage caused to the maize plant by temperatures between 0.5 to 7 °C lead to a decrease in the color of the plant and a slowdown in photosynthesis. The reduction of maize grain yield has been associated to the accumulation of persistent cold at temperatures lower than 5 °C [16,17]. If the freeze injury is not severe enough to cause the kernel black layer to prematurely form, kernels will continue to accumulate dry matter by translocating sugars from the stalk and remaining green the leaf area. Severely frost-damaged corn often has kernels more susceptible to cracking, grain that is less digestible and silage with less energy (starch), and contains more fiber than normal [24].

Figure 5 Leaf damage by freezing temperatures in the maize crop.

The sowing dates recorded in field monitoring to assess damage corresponded to fields sown from November 14, 2022 to January 6, 2023 (Table 1). According to the occurrence of temperatures lower than and equal to 4 °C, some fields were not affected, but the average damage in the 18 maize fields evaluated was 30.24 %, with a range of 0 to 81 %. Depending on the sowing date and the occurrence of the freezing temperatures, plants were affected between leaves 3th to 13th, considering that the main ear leaf was located between the 9th and the 11th; damaged plants showed a delay of around 8 to 12 days compared to the undamaged population. In relation to the percentage of foliar damage and its interaction with the grain yield, the general impact of the freezing temperatures in the 18 fields, indicated that for every 1 % of foliar damage, the grain yield was reduced by 0.0228 t ha^{-1} and the average grain yield of the fields by 1.85 t ha^{-1} (Figure 6). The escape from this environmental condition occurred in fields sown in January, the proximity to the sea such as the field in B-2914, and also in fields where irrigation coincided with the occurrence of the freezing temperatures, such as those located in B-115, B-629, and B-1123.

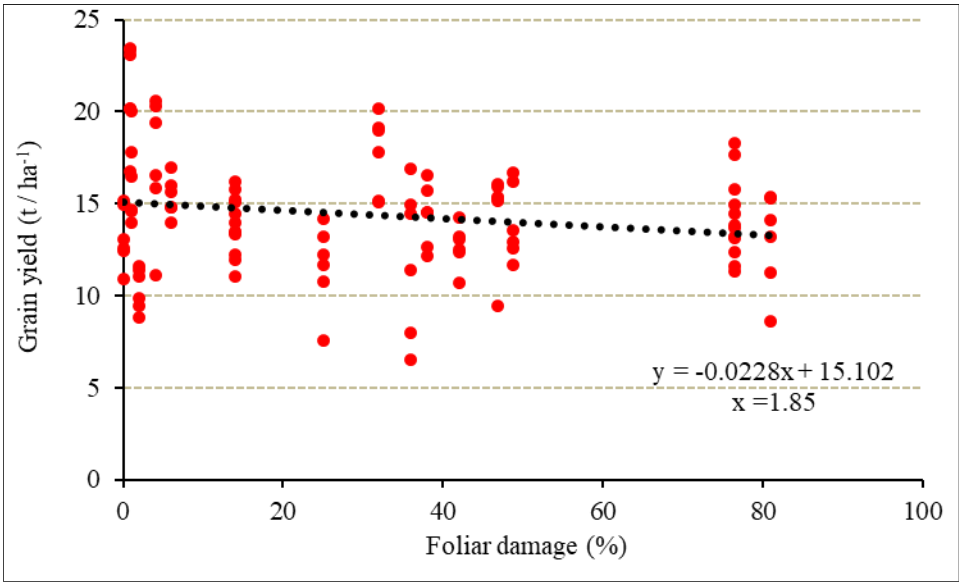

Figure 6 Correlation between foliar damage and maize grain yield in 18 commercial fields, in the Yaqui Valley, Sonora, Mexico in 2023.

As reported by Balcarce [13], the use of water is one of the oldest methods to counteract a frost. The highest yield was obtained in the field in B-1123 with 21.18 t ha^{-1} with the hybrid Hipopótamo (Table 1), which coincides with the early sowing date of November 14 and the timely application of irrigation, that served to minimize the impact of the low temperatures presented during the month of January; also, the female and male flowering took place between March 10-14 escaping the high temperatures. The fields in B-1318, B-117, and B-617 showed the highest percentage of foliar damage, which was 81 and 76.5 % for the last two fields; they were sown on December 13, 30, and 10, respectively. Fields in B-617 and B-1318 presented damage due to the impact of two occurrences of freezing temperatures during plant growth and the grain yield was affected; on the other hand, the field in B-117 showed damage in the first leaves, but the timely application of irrigation helped to minimize the effect of the freezing temperatures, and therefore, plants could later recover and thus obtain a yield of 15.32 t ha^{-1}. The effect of high temperatures was reflected in the field in B-2914, which was sown on January 06 and did not have damage by the freezing temperatures; however, grain yield was 13.16 t ha^{-1} due to the occurrence of high temperatures during flowering and development of the grain. Maize plants subjected to temperatures above 35 °C for more than eight days during reproductive development suffer a 74 % reduction in grain yield [27]. Cheikh and Jones [28] reported that for every 1 °C increase in temperature above the optimal value (25 °C), there is a 3-4 % reduction in yield. There was a significant negative impact due to late sowing, which reduced the yield by 0.0638 t ha^{-1} per day of delay, with respect to the optimal sowing date (Figure 7), and the reduction of the average grain yield was 1.53 t ha^{-1}.

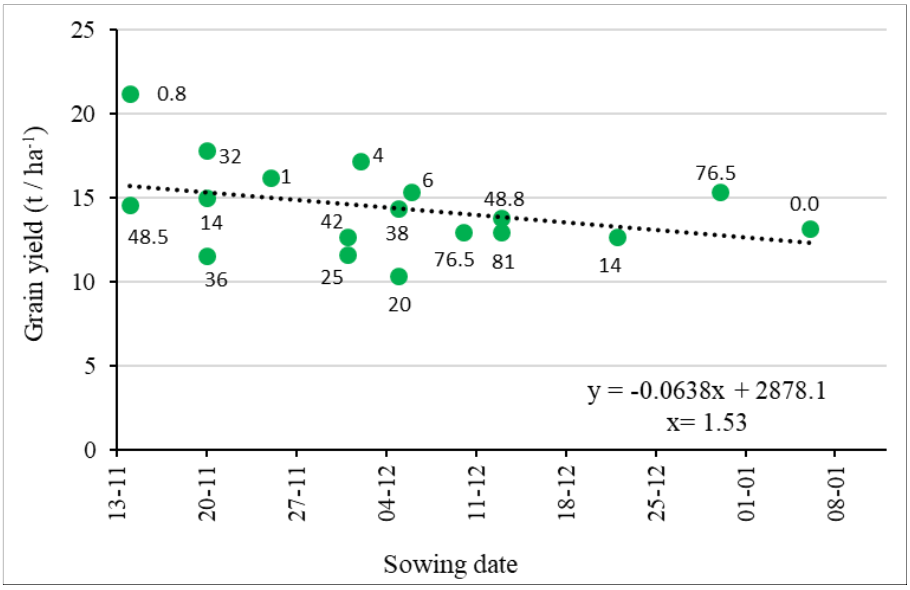

Figure 7 Correlation between sowing date and grain yield in 18 commercial maize fields, in the Yaqui Valley, Sonora, Mexico in 2023. Numbers by the green circles are the percentage of foliar damage by freezing temperatures.

4. Conclusions

Minimum temperatures lower than and equal to 4 °C from all 21 weather stations in the Yaqui Valley, Sonora, Mexico, occurred on January 3, 4, and 13. The highest number of hours of this thermal level occurred from January 22 to 25 with a range of 58 to 75 and average of 67.7.

The average foliar damage in 18 maize fields evaluated was 30.24 %.

Minor damage was related to the irrigation provided to the crop before the occurrence of the freezing temperatures.

The greatest damage was detected in fields sown early, and it was related to the phenological stages 9th to the 11th ligulated leaves.

For every 1 % of foliar damage, the grain yield was reduced by 0.0228 t ha^{-1} and the average production of the fields by 1.85 t ha^{-1}, while for late sowing, grain yield was reduced by 0.0638 t ha^{-1} per day of delay, with respect to the optimal sowing date, and the reduction of the average production of the fields by 1.53 t ha^{-1}.

Compliance with ethical standards

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

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