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REVIEW

Crop Management

Conditions potentially affecting corn ear formation, yield, and abnormal ears: A review

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Abstract

Abnormal ear development in corn (*Zea mays* L.) has been reported for more than 100 years. More recently, in 2016, widespread abnormal multiple ears per stalk node (herein termed as multi-ears), barbell ears, and short husks were reported in cornfields located in the western and central Corn Belt (Illinois, Iowa, Nebraska, and Kansas), Eastern Colorado, and the Texas Panhandle region in the United States. Little was known about the underlying causes of these abnormalities. A literature review examining conditions potentially affecting corn ear formation, yield, and abnormal ears was conducted. Several abnormal ear symptoms appear to be formed by stress conditions such as extreme weather, limited solar radiation, and responses to plant growth regulators. The accumulation of these effects can result in the abortion of primary ears and the development of secondary abnormal ears, which has been a hypothesis for the last 15 years. Whether or not primary ear abortion is one of the factors for abnormal ears remains a valid question. Abnormal ears can be understood as the result of an "expression triangle": susceptible genetics, conducive environmental conditions, and unfavorable management practices. Together, these factors can interact and cause abnormal ears and lower yields. Active knowledge gaps include the environmental and physiological pathways to abnormal ears, their impact on grain quality and yield, their effect on other processes such as dry-down and harvest ease, and an in-depth understanding of differing genetics, environment, and management.

Abbreviations: ACC, 1-aminocyclopropane-1-carboxylic acid; AE, arrested ear(s); APE, alkylphenol ethoxylate; NIS, nonionic surfactant; VE, emergence vegetative corn stage; VT, tasseling vegetative corn stage.

1 | INTRODUCTION

Corn (*Zea mays* L.) ear abnormalities have been reported for over a century (Bonnett, 1966; Emerson, 1912; Kempton, 1913). Distinct differences exist between normal and abnormal ears, one of them being the capacity to produce yield. Normal ears for hybrids in the U.S. Corn Belt can produce about 800 to 900 kernels in each ear, normally arranged in 16 or 18 kernel rows that have up to 50 to 55 viable ovules per row (Ortez, McMechan, Hoegemeyer, Ciampitti, et al., 2022). As a result of pollination issues or kernel abortion during grain formation, the number of harvested kernels per ear is generally lower. Normal ears do not present any major disruption to their cob, kernel, and husk growth and development, and they can produce higher yields (Ortez, McMechan, Hoegemeyer, Rees, et al., 2022). However, possible minor disruptions can be seen in normal ears; for example, some kernels extending beyond the husk tips, some kernels aborted in the ear tips, or husk leaves slightly open towards the tip of the ear.

In contrast, abnormal ears show distinctive disruptions in the development of their cob, kernels, or husk leaves. Abnormal ears include tassel ears (Nielsen, 2019a), arrested ears (AE) (Nielsen, 2007), ears with cob curvatures (Bryant, 2020; Thomison et al., 2020), ears without viable or exposed silks (Nielsen, 2020; Ortiz et al., 2015), ears with unusual patterns of failed pollination or kernel abortion (Nielsen, 2019b), plants with more than one ear on the same ear shank (Elmore & Abendroth, 2006; Nielsen, 2006, 2014), ears with kernel skips along the cob (Thomison et al., 2020), and ears inadequately covered by husk leaves (Nielsen, 2018). A more detailed description and visuals of these symptoms can be found in Ortez, McMechan, Hoegemeyer, Ciampitti, et al. (2022).

More recently, ear abnormalities were reported in Iowa, Illinois, and Indiana (Elmore & Abendroth, 2006; Nielsen, 1999, 2006, 2014). The most recent widespread reports of ear abnormalities occurred in the western and central U.S. Corn Belt, Eastern Colorado, and the Texas Panhandle in 2016 (Figure 1). A survey in 15 grower fields studied the factors and investigated potential causes (Ortez, McMechan, Hoegemeyer, Rees, et al., 2022). The survey results showed that (a) affected fields averaged 26% abnormal ears and ranged between 12 and 49%, (b) abnormal ears reduced grain yield by 35 to 91% (yield loss per area depends on the symptom, its frequency and severity), and (c) the placement of abnormal ears suggested that abortion of the primary ear was a correlated factor. The authors suggested that ear abnormalities resulted from cumulative interactions among genetics (e.g., hybrid-specific and variable hybrid responses), environment (e.g., stress factors), and management practices. The effect of management can be related to the crop's exposure to unfavorable conditions at different times (e.g., sensitivity levels) or creation of more or less interplant competition (e.g., differing planting dates or seeding rates), but further research is needed.

Core Ideas

- Extreme weather, low solar radiation, and growth regulators can be some of the causes.
- Primary ear abortion has been observed to correlate with the occurrence of abnormal ears.
- Factors affecting corn ear formation and abnormal ears result in lower yields.
- Genetic × environment × management interactions affect ear formation, yield, and abnormal ears.

The flowering habits of corn, including ear initiation, were investigated and described decades ago (Bonnett, 1966; Kiesselbach, 1949; Postlethwait & Nelson, 1964). Plant growth and development rely on actions executed by different meristems throughout the plants (Pautler et al., 2013; Postlethwait & Nelson, 1964), which give rise to organs such as leaves and floral structures through the plant cycle (Brukhin & Morozova, 2011). Axillary ear meristems, which potentially initiate ears or tillers, are initiated acropetally (i.e., from base to tip) at every node of the plant's stalk (Figure 2) except for the uppermost five to nine nodes (Lejeune & Bernier, 1996). In most modern hybrids grown in the U.S. Midwest, the upper one or two axillary meristems result in ears with harvestable grain (Hanway & Ritchie, 1985; Parco et al., 2020; Ross et al., 2020), although most hybrids have been bred to only develop a single ear on the corn plant (Hallauer, 1974).

The three main components of corn grain yield include ear number per unit of area, kernel number per ear, and kernel weight. These components are determined at different times during the growing season (Figure 3). Plant density, which primarily determines the ear density per area, is defined by the success of germination, emergence, and stand establishment. Ovule formation (potential kernel number) occurs during the mid- to late vegetative stages, approximately V7 through V14 (seven and fourteen collared leaves, respectively. V denotes all vegetative corn stages, VE (emergence) through to VT (tasseling); Abendroth et al., 2011). The success of pollination, kernel fertilization, and kernel retention determines harvestable kernels through to about R3 (Milk. R denotes all corn reproductive stages, R1 [Silking] through to R6 [Physiological Maturity]; Abendroth et al., 2011). Finally, kernel weight is determined during the latter half of the season from about R2 (Blister) through to R6.

The crop's exposure to unfavorable conditions during the growing season can negatively impact ear formation and yield (Jones et al., 1985; Schussler & Westgate, 1991). A review of the literature was conducted with the overall aim of identifying conditions potentially affecting corn

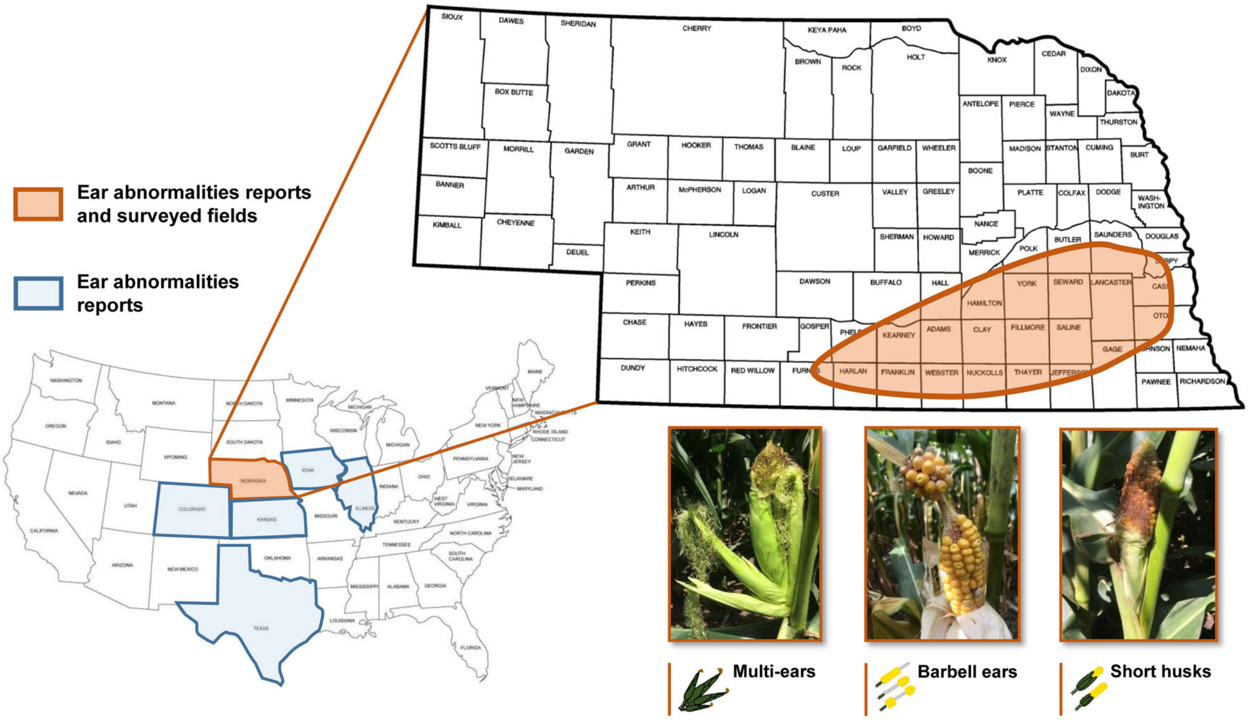

FIGURE 1 Abnormal ear development reported in 2016 across the western and central Corn Belt (Illinois, Iowa, Nebraska, and Kansas), Eastern Colorado, and the Texas Panhandle in the United States. The orange-highlighted area shows where the 15 grower fields were surveyed in Nebraska, 2016. Photo insets show examples of the reported abnormal ears: multi-ears, barbell ears, and short husks. Figure adapted from Ortez , McMechan, Hoegemeyer, Rees, et al. (2022). Inset pictures: Osler Ortez

ear formation, yield, and abnormal ears. Both environmental and physiological factors were considered. An overview of potential conditions such as extreme weather, solar radiation, plant growth regulators, and primary ear abortion is presented.

2 | EXTREME WEATHER

Corn productivity can be drastically affected by extreme weather such as drought, hail, flooding, freezing temperatures, high temperatures, and high-velocity winds. For example, widespread drought in 2012 caused a 23% loss of production in the United States relative to the yield trends (USDA-NASS, 2013). A heatwave (prolonged periods of extreme heat) from May through to July, coupled with severe drought conditions, affected the Corn Belt, compromising early growth, pollination, and water use that year. The combination of the 2012 drought and the limited availability of rain and snowfall during the subsequent months resulted in reduced soil moisture for the 2013 crop season, increasing the risk of production losses and decreasing potential yields (Chung et al., 2014).

In 2016, the widespread abnormal ear symptoms reported in Nebraska and the surrounding regions (multi-ears, barbell ears, and short husks) correlated with weather-related stress caused by temperature changes and a wind event in July that year (Elmore et al., 2016). Warm temperatures preceded high-velocity winds in July, and these were followed by a cold spell and then a period of warm weather. At that time, most Nebraska corn was in the late vegetative stages. Significant damage to the primary ears related to green snap and plant lodging were correlated with the growth of secondary and abnormally developed, ears.

Lejeune and Bernier (1996) conducted a study to evaluate the effects of environmental conditions on ear shoot initiation in three inbred genotypes of corn. One of the genotypes tested ('B22') was known for frequent abortion of its uppermost ear; it had reports of reproductive issues affecting the initiation of the uppermost ear and the ear being replaced by a sterile "leaf-like" structure by maturity (Gayral, 1991). Lejeune and Bernier (1996) reported that abortion of the primary ear could be induced by imposing a cold treatment of 10 ˚C for 5 to 7 days right before tassel initiation, around the V5 stage (Figure 3). The three inbreds differed in their response to the cold treatment, and the authors concluded that genetics were one of the factors. The authors suggested that cold temperatures can affect apical dominance, where sensitive genotypes respond by repressing axillary meristem development.

FIGURE 2 Dissected plant at the V18 stage with 18 fully developed (collared) leaves. The plant shows initiated ears at every aboveground node of the plant's stalk except for the uppermost eight nodes. Figure reproduced with permission from Abendroth et al. (2011)

Lejeune and Bernier (1996) also observed that additional factors such as high solar radiation and flooding increased the abortive response of the uppermost ear shoot (primary ear), although the further investigation was needed. Foyer et al. (1994) documented that high solar radiation coupled with additional stress, such as chilling temperatures, can cause oxidative stress in plants. On the other hand, flooding is responsible for stress-related root hypoxia and other anaerobic reactions (Perata & Alpi, 1993). Oxidative stress results from light-mediated enzyme imbalances, resulting in plant cell death (Xie et al., 2019).

3 | SOLAR RADIATION

Although light availability is critical for corn yield (Hashemi-Dezfouli & Herbert, 1992; Liu & Tollenaar, 2009; Reed et al., 1988), the potential adverse effect of a cloudy day might be small, as solar radiation conditions get better in the following days. However, an accumulation of cloudy days can lower grain yields. Elmore et al. (2019) modeled the effect of seven continuous cloudy days in central Nebraska when corn was at about the R4 stage (i.e., Dough). The Hybrid-Maize (https://hybridmaize.unl.edu/) crop model estimated that average daily solar radiation for the week of 19 to 25 August in the previous 4 years (2015–2018) was 46% higher than in 2019, resulting in an estimated yield decrease of 5.2% with the limited solar radiation in 2019.

Increased light interception in the lower plant canopy (achieved by lower plant density) increased the number of harvestable ears per plant (Prine, 1971). The study explored the effect of two semi-prolific corn hybrids and two plant densities: 22,250 plants ha^{-1} (50% plant removal at the silking stage) vs. 44,500 plants ha^{-1} (no plant removal, control). Lower plant density resulted in 1.76, 1.57, and 1.70 ears per plant in three consecutive years, whereas the high plant density resulted in 1.10, 1.05, and 1.02 ears per plant. The authors concluded that the silking stage was critical for corn growth and development, and that higher ear number per plant reflected increased light availability and interception, implying less interplant competition. After plant removal at silking, the remaining plants compensated (to some degree) the yield losses by increasing the weight of their ears. The authors indicated that plant yield losses from fewer ears in unfavorable environments could not be fully recovered by greater ear weight in the remaining ears.

Earley et al. (1966) studied the effects of various sunlight conditions on the growth and production of grain of three hybrids in Illinois. The light treatments (1954: 100% (control), 70, 40, and 10%; 1955 and 1956: 100, 70, 40, 30, 20, and 10%) were obtained with shade structures. The treatments were initiated on 2 July, 5 July, and 8 June in 1954, 1955, and 1956 resulting in 90, 72, and 113 days of treatment. The authors found a significant decrease in grain, stover, total protein, and total oil as the light availability decreased. They also found a linear reduction in whole plant (grain + stover) protein when the light availability decreased. Significant light reductions resulted in lower yields, irrespective of the hybrid tested. However, one of the three hybrids was more tolerant of light changes. Kernel number reductions occurred, and these reductions were higher with more significant light reductions. This study reported barren ears when the sunlight was reduced by 80 and 90% or more. Reducing the sunlight by 30% was enough to suppress the development of secondary ears in all three hybrids (two of which were considered prolific). The length of the shading time relative to the morphological development, and the shading duration affected the crop's responses.

A year later, in Illinois, Earley et al. (1967) studied light reductions (through shading) during the vegetative, reproductive, and morphological maturation phases of two corn hybrids. One of the main findings was that shading resulted in significant reductions in all components measured (morphology, grain yield, and chemical composition) except those started prior to treatment initiation. The authors found that 21 days of shading at the reproductive phase was more detrimental to grain production per plant than shading for more

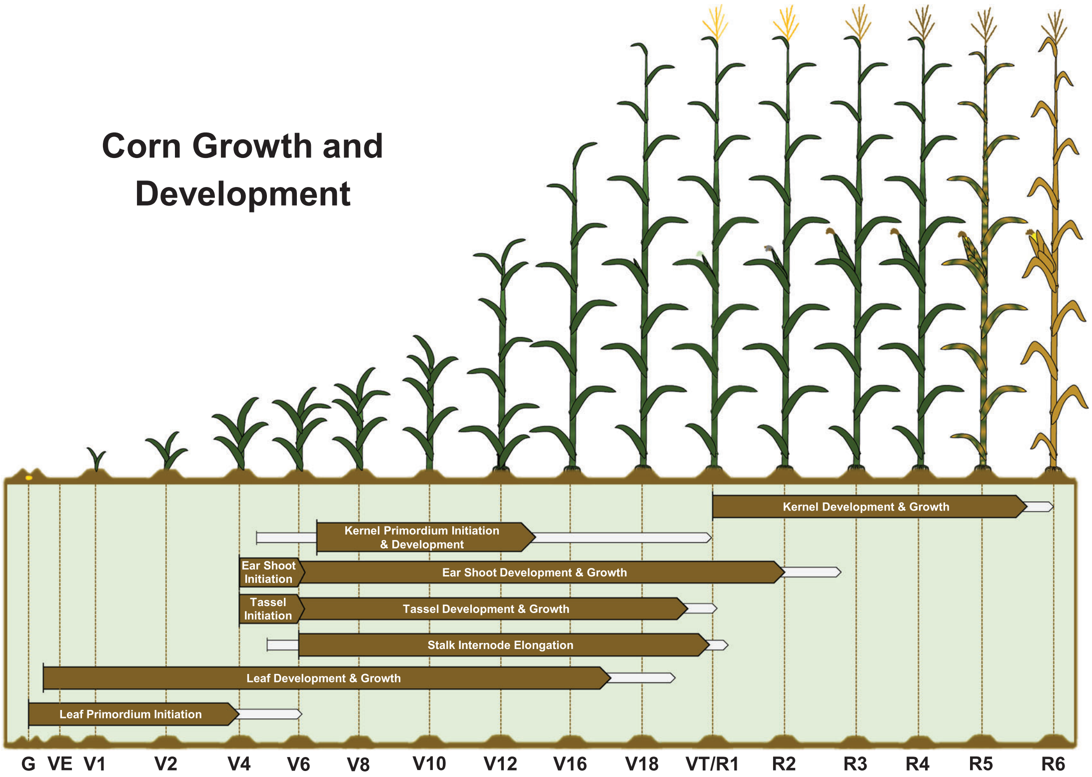

FIGURE 3 Initiation and growth period for aboveground plant structures extending from germination (G) to physiological maturity (R6). According to literature reports, the horizontal brown arrows indicate the main period when the event occurs, and the thin horizontal gray arrows indicate possible time variations for each event.The ear shoot initiation arrow refers to the initiation of primary ear shoots. Kernel primordium initiation refers to the initiation of florets which may form kernels if properly developed, pollinated, and fertilized. Figure adapted from Abendroth et al. (2011), McMaster et al. (2005), and McMechan et al. (2017)

extended periods at either the vegetative or maturation phases. Their results showed that 60, 70, 80, and 90% shading between 17 July and 7 August produced barbell-shaped ears and AE. Earlier (25 May–17 July) or later (7 August–2 October) periods of shading resulted in incomplete kernel setting (scattered kernel skips). In their findings, the early shading treatment of 90% was conducive to banana-shaped ears.

Later, Earley et al. (1974) studied the ear shoot development of Midwest dent corn. Their studies included trials that stimulated nonfunctional ear shoots; 90% shading of plants around silking time was one of the studied treatments. Two hybrids were shaded for 6 consecutive days, and different shading treatments were applied on 13 July and ended on 17 August. The average silking date for the studied hybrids was 29 July and 31 July. The results showed barbell ears when the shading treatment corresponded to 19 July to 24 July, 25 July to 30 July, or 31 July to 5 August. These findings suggested that 90% shading can result in barbell ears when shading occurs before, during, or right after the silking time of corn in the U.S. Midwest. When 90% shading occurred for an extended period (from 8 June–28 September), most ears failed to develop (i.e., ear abortion).

4 | PLANT GROWTH REGULATORS

Plant hormones control several aspects of plant growth (Ross & O'Neill, 2001). Plant growth regulators have been reported as both inhibitors and promoters of flowering in some species considered to be photoperiodic (Lejeune et al., 1994) and of axillary meristem formation (Cline, 1994; Mok, 1994). Plant growth regulators, abscisic acid, and ethylene are typically involved in plants' responses to stress. It has been reported, particularly for corn, that when auxinic compounds are applied at the floral transition stage (approximately between V4 and V6), the likelihood of ear shoot abortion increases (Lejeune et al., 1998). Lejeune et al. (1998) reported (a) abortion of the uppermost ear when the chilling treatment was applied just before floral transition, (b) ear abortion caused by chilling was reduced with applications of cytokinins before floral transition, and (c) cytokinin applications before floral transition promoted axillary meristem activity at nodes above the primary ear node and thus resulted in more ears reaching silking. These findings suggest that cytokinins could positively affect corn yields and prolificacy.

In a different report, when auxinic compounds were applied before the silks emerged, parthenocarpic kernels (i.e., kernels that were empty, lacked an embryo, or were nonviable) resulted, which led to malformed ears (Earley et al., 1974). Applications of ethephon, an ethylene-based growth regulator, decreased kernel number per ear (Cox & Andrade, 1988). An in vitro study by Hanft et al. (1990) suggested that the precursor of ethylene, 1-aminocyclopropane-1-carboxylic acid (ACC), could be responsible for kernel growth inhibition in corn. Hence, plant growth regulators are essential in determining plants' responses to stress, ear formation, yield, and primary ear abortion in corn.

Cheng and Lur (1996) investigated kernel development and carbohydrate changes, ACC, and ethylene. Ethylene was induced by reducing 70% of light availability (with shading), imposing plant stress in field and greenhouse trials. The light reduction started 1 or 2 days before pollination (VT or R1), and plants were shaded for 10 to 11 days. Their findings showed that (a) shading reduced the photosynthetic rate from 24 to 4 µmol CO_2 m^{-2} s^{-1}, (b) the apical (30% of total ear length, measured from the tip) and basal (lower 50% of the total ear length, measured from the base) kernels of shaded plants had greater concentrations of glucose than those of the control plants, (c) the apical kernels of shaded plants had lower sucrose concentrations than those of the control plants, and (d) both kernel regions (apical and basal) of shaded plants had less starch content than the control plants. These effects led to a decrease in kernel weight and subsequent kernel abortion, especially in the apical portion of the ears.

Kiniry and Ritchie (1985) documented that kernels abort when dry weight accumulation ceases during early kernel development. In addition, Setter and Flannigan (1989) reported a significant increase in ACC levels for shaded plants in both apical and basal regions of the ears, related to an increase in ethylene. In their findings, shading the plants also caused reductions in endosperm nuclei numbers. Hanft et al. (1990) suggested that ethylene might be responsible for stimulating the carbohydrate levels of stressed plants. Bollmark and Eliasson (1990) indicated that ethylene may be responsible for the breakdown of cytokinins, which are important for endosperm cell division and the development of kernels when plants are under stress. Setter and Flannigan (1989) found that ethylene may be the factor involved with corn kernel abortion, at least under light-limiting conditions. All these authors agreed that the relationship between ethylene and kernel abortion resulting from other sources of stress (e.g., water shortage, wind damage, extreme heat, and cold temperatures) had to be studied further.

In a recent study, Ning et al. (2021) studied ethylene's influence on variations in corn ear length and grain yield. Their study included molecular work that identified the gene associated with ethylene changes. Editing that gene confirmed the reduction of ethylene in the developing ears, and it was able to promote flower and meristem development. Their study resulted in a 13.4% increase in yield for each ear in the studied hybrids. They concluded that ethylene is an essential signal for inflorescence development, affecting spikelet number, floral fertility, kernel number, and ear length. The authors indicated that fine-tuning ethylene levels could represent a tool for improving corn productivity and also be expanded to other cereals.

Furthermore, ethylene has been associated with fruit abortion in cotton (*Gossypium hirsutum* L.) (Guinn, 1976) and wheat (*Triticum aestivum* L.) (Hays et al., 2007; Narayana et al., 1991) when plants experience stress. The exposure of heat-susceptible hard red winter wheat plants to heat at the early kernel development stage resulted in a sixfold increase in ethylene in kernels (Hays et al., 2007). The increase in ethylene was also reported in embryos and the flag leaf; these effects correlated with increased kernel abortion and a reduction in kernel weight among the kernels retained. In this experiment, a heat-tolerant cultivar of hard white spring wheat was also evaluated, and no change in ethylene was observed after the application of heat. The authors presented evidence that ethylene was one of the drivers regulating plants' susceptibility to heat stress and kernel abortion. When an ethylene receptor inhibitor (1-methyl cyclopropane) was used in their trials, the developmental responses to high temperatures were suppressed, suggesting that ethylene is a significant factor in heat or high-temperature stress in plants.

Ethylene and alkylphenol ethoxylate (APE) share ethylene oxide as a biological metabolite (Dodds & Hall, 1982; Jones & Westmoreland, 1998; Ying et al., 2002), and APE is a common component of nonionic surfactant (NIS) (Schmitz et al., 2011). Foliar application of NIS resulted in AE development when applied at the V10 to V14 development stages (Schmitz et al., 2011). Their results documented that (a) NIS formulations containing APE applied between the V10 and V14 stages resulted in maximum AE, (b) hybrids differed in their responses to AE, (c) strong relationships existed between AE and lower yields ($r = 0.88$, $P < .001$), and (d) AE was positively correlated with precipitation from planting to the V14 developmental stage ($r = 0.86$, $P = .061$). The authors speculated that the reason for AE's correlation with precipitation is that more precipitation increased biomass and promoted thinner leaf cuticles, possibly increasing the chemical absorption rates.

Other researchers also reported AE issues caused by foliar NIS applications (Below et al., 2009) coinciding with the period of silk initiation in plants, which is around V11 to V13 (Stevens et al., 1986). Below et al. (2009) reported the occurrence of AE (which they referred to as hollow husk) caused by foliar applications made between V11 and V15, which presumably caused changes in the ethylene concentration in the plant. They found that the percentage of plants with AE depended on the hybrid, the stage of plant development when the foliar applications were made, and the management conditions that promoted faster plant growth. Furthermore, they observed that AE increased with a higher nitrogen supply and decreased at higher plant populations.

In 2019, a pivot-irrigated field in Nebraska planted to a commercial corn hybrid showed >50% of plants with abnormal ears (Elmore, Rees, Sosa, and Ortez, unpublished data, 2019). Several abnormal ears (multi-ears and short husks for the most part) were secondary ears on plants with AE in the primary ears. These abnormalities were thought to result from a foliar application that included NIS in the formulation around the V13 stage. The rainfed corners of the field had fewer abnormalities, with less than 30% of affected ears, which supported the water availability explanation of Schmitz et al. (2011). The AE issues caused by NIS foliar applications have been well documented; the current recommendation for reducing the risk of AE occurrence is to avoid applying APE-containing NIS between the V8 and VT growth stages in corn (Below et al., 2009; Rees et al., 2020; Schmitz et al., 2011; Stetzel et al., 2011).

5 | PRIMARY EAR ABORTION

After the occurrence of abnormal ear symptoms in 2006 and 2016, it was hypothesized that the abnormal ear issues could be correlated with the loss of the primary ear (Elmore & Abendroth, 2006; Elmore et al., 2016; McMechan et al., 2017; Ortez et al., 2019). Nielsen (2014) noted that injury to the primary ear before pollination or the failure of pollination in the primary ear was correlated with the expression of multi-ears. Occasionally, the upper ear shoot aborts. Abortion of the primary ears can occur in response to extreme weather and growth regulator changes in the plant (Lejeune et al., 1998). When the primary ear aborts, the secondary ear will often develop into a harvestable or malformed ear.

Individual ears initiate acropetally from axillary meristems at the stalk nodes. The ear initiation process coincides with tassel initiation (Figure 3) at approximately the V4 to V6 stages (Abendroth et al., 2011; Alter et al., 2016; McMaster et al., 2005; Stevens et al., 1986). The uppermost ear typically develops into the harvestable ear (Abendroth et al., 2011; Stevens et al., 1986). For modern U.S. Corn Belt hybrids, the primary ear is located at Nodes 12, 13, or 14 (Abendroth & Elmore, 2009). Although the lower ear shoots form first, the primary ear shoot becomes apically dominant, resulting in slower growth in the lower shoots.

Earley et al. (1974) and Freeman (1940) reported the initiation of axillary buds and the formation of ear shoots on the same ear shanks (i.e., multi-ears). On the basis of the field results, Earley et al. (1974) pointed out that the primary ear has to be removed, covered, or partially damaged around or before the silking time for the plant to produce multi-ears. Their results showed that multi-ears could develop from different hybrids at the primary and secondary ear nodes. In their study, removing the first functional ear shoots between 4 and 12 August resulted in barbell ears, with missing kernels and underdeveloped cobs in the lower sections of the ears.

6 | CONCLUSIONS

Despite the outlined review and summary of the available literature in this article, several complexities and questions still need answers about the dynamics driving ear formation, yield, and abnormal ears. With the knowledge available, one can view abnormal ear development from an "expression triangle" perspective, where susceptible genetics, conducive environmental conditions, and unfavorable management practices can result in abnormal ears. A classic and well-documented example of this expression triangle is the previously described occurrence of AE. The crop's exposure to unfavorable conditions can negatively affect ear formation and produce abnormal ears. Abnormal ears decrease yield and can reduce grain quality.

The understanding of abnormal ears must include identifying when the potential stress occurs relative to an ear's formation. Ear abnormalities can result from physiological changes in response to genetics, the environment, and management. Abnormal ears appear to develop as a result of stress conditions such as extreme weather, limited solar radiation, and plant growth regulator changes in the plant. These stresses can result in the abortion of primary ears and the subsequent development of abnormally developed ears at lower stalk nodes. Whether or not primary ear abortion is one of the factors involved remains a valid research question. Several knowledge gaps persist because of the random distribution and hard replicability of abnormal ear symptoms.

Future research is needed to expand our understanding of the environmental and physiological pathways to abnormal ears and the subsequent lower yields. Beyond yields, research can also look at the impact of abnormal ears on grain quality (e.g., mycotoxin levels, test weights, protein content) and other processes such as grain moisture dry-down and harvest ease (e.g., short husks or lower ears). Field research would help to understand the effect of genetics (e.g., the identification of susceptible versus check hybrids), environments (e.g., rainfed versus irrigated or cooler versus warmer), and management combinations (e.g., lower or higher competition, seeding rates, and planting dates) in broad (e.g., canopy-level) and narrow (e.g., plant-level) scales. Studies under controlled environment conditions (e.g., greenhouses, growth chambers) can offer robust opportunities to understand various stress sources such as cold, heat, and growth regulators (e.g., ethylene) and their effects during critical or sensitive stages for corn growth and development. Focused studies on the contributing effects of other adverse weather events such as wind, hail, or flooding events would also be important.

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AUTHOR CONTRIBUTIONS

Osler Ortez: Conceptualization; Funding acquisition; Investigation; Writing – original draft; Writing – review & editing. Justin McMechan: Conceptualization; Funding acquisition; Supervision; Writing – review & editing. Thomas Hoegemeyer: Conceptualization; Writing – review & editing. Ignacio Antonio Ciampitti: Conceptualization; Writing – review & editing. Robert L. (Bob) Nielsen: Conceptualization; Writing – review & editing. Peter Thomison: Conceptualization; Writing – review & editing. Lori Abendroth: Conceptualization; Writing – review & editing. Roger W. Elmore: Conceptualization; Funding acquisition; Supervision; Writing – review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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