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Scientific review

IMPACTS OF CLIMATE CHANGE, FORMS, AND EXCESS OF NITROGEN FERTILIZERS ON THE DEVELOPMENT OF WHEAT FUNGAL DISEASES

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Background. *Global climate change and excessive nitrogen application has become a significant issue and inevitably threatens sustainable wheat production, not only with direct negative effects on crop growth but also with profound impacts on biology and pest and disease management.*

Purpose. *This review addresses the current challenges, namely the negative effects of climate change and the forms and excess of nitrogen-rich fertilizers on the development of fungal diseases in wheat, as well as management strategies.*

Materials and methods. *To achieve the stated objective of the study, the scientific literature published during the last 20 years on the impacts of climate change and the forms and excesses of nitrogen fertilizers on the development of fungal diseases and on the yield of wheat were reviewed.*

Results. *Thus, in mitigating these challenges, it is necessary to optimize the dose of nitrogen fertilizers, apply nitrogen in the form of nitrate, ammonium sulphate, ammonium nitrate, and coated urea fertilizers, to use silicate fertilizers such as calcium, magnesium, and potassium silicate, and to perform a long rotation of wheat through perennial legumes and leguminous crops, as well as to develop, through genome editing, varieties with high yield potential, resistant to biotic and abiotic stresses, and of good end-use quality, or plant new cereals that have needs for heat and a longer reproductive growth period.*

Conclusion. *To develop an effective agricultural management strategy, future research should be based on the study of the interactions among crops, pests, pathogens and farming system under climate change, taking into account all parameters such as temperature increase and CO2, extreme precipitation, etc. A sufficient number of results must be published to be able to draw meaningful conclusions.*

Keywords: *challenges; fungal diseases; wheat; nitrogen fertilizers; climate change*

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Обзорная статья

ВЛИЯНИЕ ИЗМЕНЕНИЯ КЛИМАТА, ФОРМЫ И ИЗБЫТКА АЗОТНЫХ УДОБРЕНИЙ НА РАЗВИТИЕ ГРИБКОВЫХ ЗАБОЛЕВАНИЙ ПШЕНИЦЫ

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Обоснование. *Глобальное изменение климата и чрезмерное применение азота стали серьезной проблемой и неизбежно угрожают устойчивому производству пшеницы не только с прямым негативным воздействием на рост культур, но и с серьезным воздействием на биологию и борьбу с вредителями и болезнями.*

Цель. *В этом обзоре рассматриваются две текущие проблемы, а именно негативное влияние изменения климата и формы и избытка богатых азотом удобрений на развитие грибковых заболеваний пшеницы, а также стратегии управления.*

Материалы и методы. *Для достижения заявленной цели исследования было проведено изучение опубликованной научной литературы за последние 20 лет о влиянии изменения климата, формы и избытка азотных удобрений на развитие грибковых болезней и на урожайность пшеницы.*

Результаты. *Таким образом, для решения этих текущих проблем необходимо оптимизировать дозу азотных удобрений, вносить азот в виде селитры, сульфата аммония, аммиачной селитры и карбамидных удобрений в оболочке, использовать силикатные удобрения, такие как силикат кальция, магния и* *калия, а также осуществлять длительный севооборот пшеницы с многолетними бобовыми травами и зернобобовыми культурами. Вывести путем редактирования генома сорта с высоким потенциалом урожайности, устойчивые к биотическим и абиотическим стрессам и хорошего качества для конечного использования, или возделывать новые зерновые, которые нуждаются в тепле и имеют более длительный период репродуктивного роста.*

Заключение. *Чтобы разработать эффективную стратегию управления сельскохозяйственным производством, будущие исследования должны быть основаны на изучении взаимодействия между сельскохозяйственными культурами, вредителями, патогенами и системой земледелия в условиях изменения климата, принимая во внимание все параметры, такие как повышение температуры и СО2, обилие осадков и т. д. Необходимо опубликовать достаточное количество результатов, чтобы можно было сделать осмысленные выводы.*

Ключевые слова: *проблемы; грибковые заболевания; азотное удобрение; пшеница; изменение климата*

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Introduction

Wheat is the most widely grown crop in the world, grown on 217 million hectares per year with a total world production exceeding 700 million tons, due to many qualities favorable for human nutrition. About 44% of the total world wheat production is produced in Asia, 34% in Europe, 15% in America, and 3.4–3.5% in Oceania and Africa [19]. China, India, and Russia are the three largest producers, accounting for around 41% of total global wheat production [19].

Despite the relatively large acreage of this crop, wheat production remains insufficient with production potential and growing demand, partly due to population growth. This is mainly due to the prevalence of several fungal diseases which are explosive, such as septoria, blotch, *Fusarium* wilt, *Rhynchosporium* wilt, powdery mildew, and rust, which largely contribute to the substantial loss of both yield, up to 15 to 20%, even more than 60% under conditions favorable to the development of these various pathogens, and grain quality by the presence of *Fusarium* mycotoxins [15, 32, 42, 48]. The development of these diseases is favored by the cultivation methods practiced, such as intensive monoculture, debris and crop residues, as well as sensitive varieties. This is further accentuated by climate change, characterized by increased temperatures and droughts or sometimes flooding, and combined with pests and other diseases, making agricultural production less predictable [54].

The consequences of climate change will undoubtedly affect not only the spread of harmful and beneficial micro-organisms, their bio-ecological properties, and relationships with plants but also the existing management options (effectiveness and duration of pesticides) and the biological factors of the host plant [27, 31, 37]. Thus, in plots inoculated with *Fusarium culmorum*, yield losses were around 15% under wet conditions and 25% under drought conditions in Tunisia (Table) [7]. In addition, contrary to oidium, high temperatures favor the growth of uredomycelium of *Puccinia graminis* and a temperature of up to 25 °C–30°C stimulates the production of spores by Ug99 of wheat, and therefore, a warming climate only reduces it in tropical regions [43]. Elevated CO_2 levels not only increased the susceptibility of wheat varieties but also increased the virulence of *Zymoseptoria tritici* and *Fusarium graminearum*, resulting in more severe disease overall [56]. In the last 10 years, due to climate change, *Fusarium graminearum*, *Pyrenophora tritici-repentis*, *Septoria tritici*, and other pathogens have appeared recently in many wheat-growing regions in Russia [31].

Extreme temperature swings during particular developmental phases, such as the blooming stage and the grain filling phase, have an impact on the weight and size of wheat grains at the end of the season. Thus, according to Nuttal et al. (2012), wheat production decreased by 13% and most grains were sterile at 36 ± 2°C during flowering [40]. In addition, according to Asseng et al. (2015), for every 1°C increase in temperature, global wheat production is projected to decrease by 6% and become more spatially and temporally variable [2]. Similarly, Rettie et al. (2022) found that a 6°C increase in temperature reduced wheat grain yield by 47-57% in Ethiopia and 28-37% in Europe [46].

Nitrogen remains the determining element for the production of cereals, and its efficient use is decisive for the improvement of production in quantity and quality. However, the nature, dose, and telluric phytosanitary aspect of wheat, as well as the form and climatic condition in which nitrogen must be applied, is a significant challenge in wheat production [16, 17, 18, 32]. Thus, high doses of nitrogen increase the severity of stripe rust [14], stripe rust [32], powdery mildew and septoria leaf spot [7, 32], and *Fusarium* wilt [16, 18]. In three greenhouses with different environments, the use of nitrogen at a dose of $24gL^{-1}$ favored the incidence and development of collar rot induced by *Fusarium culmorum* and significantly reduced the yield of durum wheat by 76 % relative to the $1.5gL^{-1}$ dose [18]. The application of nitrogen at a dose of 24 g L-1 induced an increase in severity of 127%, 179% and 280% respectively for durum wheat, soft wheat and barley (Table) [18]. Similarly, unlike urea-based fertilizers, the use of ammonium nitrate significantly controlled *Fusarium culmorum* [16, 18]. Information on these challenges will be of great importance for building integrated science-based plant protection systems and improving soil fertility [31]. For this purpose, this review was interested in studying the impacts of climate change and the forms and excess of nitrogen-rich fertilizers on the development of wheat fungal diseases and their management strategies.

Table.

Impacts of climate change and excess dose of nitrogen fertilizer on the development of wheat fungal diseases

Pathogens	Factors	Quantity	Impacts	Location	Country	Sources
F. culmorum	Dryer season	294 mm	Yield losses (25%)	Greenhouse test	Tunisia	Chekali et al., 2013
	Wetter season	524 mm	Yield losses (15%)			
	Urea	24 g L-1	Yield losses (76%)	Greenhouse test	Morocco	Eddine et al., 2022
			The severity of the crown rot (179%)			
P. graminis f. sp. tritici	Warmer climate with lower relative humidity and enhanced turbulence		Increase in the urediniospore emitting potential of an infected field as global average ~40%	Field test	Europe, Asia, America and South Africa	Prank et al., 2019
B. graminis f.sp. tritici	Nitrogen fertilizer	90-270 $kg \cdot ha^{-1}$	The severity on average (77.0-154.7%)	Field test	China	Luo et al., 2021
P. striiformis f. sp. tritici			The severity on average (37.8-350.2%)			
B. graminis f.sp. tritici		112.5-337.5 $kg \cdot hm^{-2}$	Disease severity index (92.5-217.0%)	Field test	China	zhu et al., 2017
Z. tritici	Nitrogen fertilizer	50-150kg. ha^{-1}	Stimulation and amplification of disease incidence	Field test	Tunisia	Ben Omrane, 2020
B. graminis f.sp. tritici	Low temperatures and ambient CO_2	18–22°C and450 ppm	The highest pathogen quantity was 40 µg of *B.graminis f.sp. tritici*/g fresh weight of leaves	Single phytotrons	Italy	Blandino et al., 2020

Climate change's impact on the emergence and control of wheat fungal diseases

Global climate change has recently become a significant issue and inevitably threatens sustainable wheat production, not only with direct negative effects on crop growth but also with profound impacts on biology and pest management. According to Asseng et al. (2015), for every 1°C increase in temperature, global wheat production is projected to decrease by 6% and become more spatially and temporally variable [2]. Similarly, the yield loss for each 1°C increase in global average temperature is about 6.0% for wheat, 3.2% for rice, 7.4% for maize, and 3.1% for soy [62]. A 1% increase in average growing season temperature could result in a 0.109% loss in winter wheat yield per unit area, while a 1% increase in growing season precipitation could result in a 0.109% loss in winter wheat yield per unit area of the latter by 0.186% when the other factors remain constant according to the Cobb-Douglas production function [23]. In addition, under normal conditions for the 2014-2015 campaign, the economic losses generally amounted to 344 and 243 million dollars, respectively, for the national production of durum wheat (2.4 Mt at 266 dollars/ton) and common wheat (5.6 Mt at 221 dollars/ton). But for a dry year like the 2015–2016 agricultural campaign, losses due to drought reached 317 and 718 million dollars, respectively, for durum wheat (0.9 Mt at 211 dollars/ton) and common wheat (1.9 Mt at 194 dollars/ton), and this compared to a normal year [20, 34].

An increase in CO_2 significantly reduced the total fecundity of cherry oat aphids to 22% and wheat N content to 39%, contrary to an increase in nitrogen, which would improve this [38]. Since aphids are vectors of viruses in wheat, any factor favoring their development may simultaneously increase the appearance and spread of viruses in the crop. The climate change scenarios, i.e. a temperature variation of +0.5 to 2.5°C and precipitation of -5 to -25%, significantly reduced the grain yield of wheat in the provinces of Mazandaran and Khuzestan but increased it in East Azerbaijan province [39]. In addition, the application of nitrogen fertilizer could not compensate for grain yield losses related to climate change [38, 39]. Here we can suggest that a variation in CO_2, temperature, and precipitation reduces the effectiveness of other wheat development factors, such as nitrogen.

Climate change manifests itself in frequent dry years and abrupt changes in weather patterns during the season. In general, the biology of pathogens and pests (survival rates, spread, infection of plants, development of the disease, reproduction of the pathogen, vectors, reserve plants, antagonists, and competitors of the pathogen), including existing management options (effectiveness and duration of pesticides) and host plant biological factors, is more or less directly influenced by temperature, rainfall, humidity, light quality and quantity, and wind [27, 31, 37]. However, a change in temperature and other climatic conditions, such as a change in precipitation, can lead to various changes related to wheat pathogens, which generally include range expansion, seasonal phenology, virulence, and population dynamics [3, 37, 57]. This may ultimately result in a change in the incidence and severity of disease at a given location and should be offset by a corresponding increase in treatment efforts seen by changes in expenditure.

Preventing or controlling wheat pests and diseases in the context of climate change is a big challenge because wheat is inevitably infected by a large number of pathogens with different development factors and which are constantly increasing each year. For example, heavy rainfall and a dew phase throughout the vegetative growth period of wheat in the spring favor the development of *Zymoseptoria tritici*, unlike *Fusarium* species, which only require rainfall of about 2–3 mm during flowering, and *Puccinia triticina* only needs night dew [47]. Similarly, *Pythium* species greatly prefer moisture; *Bipolaris sorokiniana*—hot, dry soils*; Tilletia laevis*—cold, moist conditions; *Rhizoctonia cerealis*—dry, sandy soils; cold and high humidity [3]. In short, each change in climatic conditions favors the development of organisms harmful to crops. To predict the potential development of a particular disease under new environmental conditions, it is necessary to pay close attention to a detailed study of the temperature requirements for each stage of the pathogen. This is also important because different scenarios of global warming are expected [31].

Several studies have sought to assess the effects of several factors—increased temperatures, CO_2, and changes in water or humidity conditions—on the incidence and severity of phytopathology, with study methods ranging from simple equations to complex models such as DSSAT (America), APSIM (Australia), and CCSODS (China) [23, 27]. Thus, by applying an earth system model, Prank et al. (2019) showed that a warmer climate with lower relative humidity and increased turbulence may lead to an increased urediospore emission potential of *Puccinia graminis f. sp. tritici* at 40% in the field of infected wheat (Table) [43]. The infection increased up to two times after inoculation with *Puccinia striiformis f. sp. tritici* from wheat plants grown at 12°C during the dark period and at 18°C or 25°C during the light period and transferred to the lower daytime temperature. Similarly, increased resistance when plants experienced increased temperatures was observed in seedlings and manifested as reduced hyphal colonization compared to seedlings maintained at cooler daytime temperatures. This temperature sensitivity is genotype-dependent in wheat seedlings [11]. The most favorable conditions for the progression of powdery mildew on wheat were low temperatures ranging from 18–22°C and ambient CO_2 (450 ppm) when healthy plants inoculated with *Blumeria graminis f. sp. tritici* were exposed to phytotrons. High temperatures ranging from 26 to 30°C inhibited the growth of pathogens, while high CO_2 content did not stimulate the development of powdery mildew but impaired plant vitality [36]. On the other hand, an increase in CO_2 levels favored the development of powdery mildew, leaf rust, and stem rust in susceptible wheat varieties [8]. For all wheat cultivars grown at high CO_2 in the field, grain yield increased (+16%), protein content decreased (-7%), accompanied by a reduction in dough strength, and the deoxynivalenol content increased significantly in ordinary bread-making cultivars, although the sign of *Fusarium* head blight was not noticed [9].

With the current effects of climate change, it is expected that new pests and diseases will appear, causing a change in the frequency of pathogen isolation. As evidenced by recent outbreaks of stem rust strain Ug99 in Uganda, Ethiopia, South Africa, Iran, Russia, Germany, the United Kingdom, Sweden, Denmark, and Sicily [54], and stripe rust in Central and West Asia and North Africa [43]. In addition, in recent years with increasing temperatures and drier conditions, the frequency of *Fusarium culmorum* isolation has decreased and that of *Fusarium graminearum* has increased in the UK, the Netherlands, northern Germany, and northern Poland. On the other hand, that of *Fusarium graminearum* is decreasing in several European countries and that of *Fusarium poae* is increasing significantly [37]. Also, in recent years, in the conditions of the Republic of Udmurtia, the increase in snow mold and sclerotinia in winter crops is associated with global warming and increased precipitation in autumn and winter [55]. However, when the ambient temperature changes, a change in species dominance can occur [31]. In 2017, the significantly below-average rainfall and above-average temperatures observed in January 2018 caused water stress and favored the invasion of Fall Armyworms, which were detected in all countries of Southern Africa except Lesotho and Mauritius [20]. Strong winds due to climate change were shown to transport stem rust spores within 3 days between North America and Europe, reaching Australia from South Africa, Africa from South America, and South America from New Zealand [43]. However, long-term changes in disease onset must inevitably lead to adjustments in future breeding strategies for resistance, where the stability and durability of disease resistance under heat and water stress will be important for the future. In general, it would be important to focus on resistance genes and quantitative trait loci that are not temperature-sensitive [37].

Indirect effects are mediated by host plant physiology and/or climate change-induced crop management adaptations, such as the introduction of irrigation, the abolition of soil turning operations to achieve conservation agriculture, and shifting sowing dates, for example, due to accelerated crop development [37]. At excessive temperatures, winter wheat tends to proliferate, which weakens its resistance to cold and also shortens its growing season, causing a reduction in grain weight and affecting grain quality. According to Tuktarova (2019), in the Republic of Udmurtia in Russia, the sowing time of winter crops should be postponed to a later period (by 7–10 days) compared to the recommendations given in 1970–1980 [55]. Similarly, in Iran, late sowing dates in November, December, and January improved wheat yield [39].

Effects of nitrogen fertilizer forms and excess on wheat fungal diseases

The influence of fertilizers extended not only to cultivated plants but also to the defeat of their diseases and the environment. Since the 1990s, several studies have shown that excessive nitrogen application can have a direct impact on stripe rust and powdery mildew infection and disease severity due to an increase in the density of the canopy, which provides a favorable microclimate for the development and propagation of pathogenic fungi, and also an increase in the nitrogen content of the host tissue by acting as a substrate for the growth of pathogens [14, 26, 32]. In addition, various forms of N can induce changes in physiological or biochemical processes, such as nutrient uptake, photosynthetic, respiratory and enzymatic activity, osmoregulation, and signaling pathways, which may be responsible for these tolerance mechanisms or the persistence of the host plant, thus influencing crop yield [25, 26].

Thus, unlike nitrate (NO_3^-), a low (2 mmol/L) or high (10 mmol/L) N rate in the form of ammonium (NH_4^+) reduced wheat biomass by 54% or 85%, respectively [25]. Ammonium also significantly reduced the content of K^+, an important osmotic agent, which would have a particular effect on the water status of wheat plants [25]. Indeed, wheat, like sugar beets, beans, tobacco, and canola, grows preferentially on NO_3^- nutrition, while rice, pine, and larch grow preferentially on NH_4^+ nutrition [25]. Ghafoor et al. (2021) also showed that coated fertilizers improved wheat growth and development, physiology, yield, and nitrogen use efficiencies [24]. Thus, compared to monotypic urea, urea coated with bioactive sulfur with nitrogen at 130 kg/ha significantly increased: the chlorophyll content by 55.0 (unit value), the net rate of leaf photosynthesis

(12.51mol CO_2 m-^{2} s-^{1}), and leaf area index (5.67); partial factor productivity (43.85 Kg grain Kg-1N provided), nitrogen harvest index (64.70%), and partial nutrient balance (1.41 kg grain N content Kg-1 N provided); maximum total dry matter 14402 (kg/ha); 1000 grain weight (33.66g), number of grains per ear (53.67), grain yield (4457 kg/ha) and harvest index (34.29%) [24]. In addition, by improving nitrogen uptake by plants (22.17%), coated urea fertilizers inhibited nitrification and ammonia volatilization processes [24]. These results agree with those of Shivay et al. (2016) [51].

Lyu et al. (2022) also showed foliar applications of urea and, in particular, of NO_3^- increased the filling of wheat grain in N compared to those of NH_4^+. This increase was related to the remobilization of N by NO_3^- and urea from the source organs to the grain. Indeed, NO_3^- and urea at 20–28 days after anthesis up-regulated genes control gluten protein synthesis and disulfide bonds, contributing to increased grain protein content and quality [33]. In addition, cover fertilization based on urea applied at a dose of 24gL^{-1} at the tillering and bolting stages significantly increased the severity of the disease induced by *Fusarium culmorum* under greenhouse conditions, with a significant reduction in the dry biomass of durum wheat plants compared to the other forms tested, in particular ammonium sulphate and ammonium nitrate [16]. Moreover, the urea form supported the growth, sporulation, and pathogenicity of *Fusarium culmorum*, especially at a temperature of 20–25°C, and its use at a dose of 24gL^{-1} biased varietal resistance [17].

Increased N levels increased the severity of stripe rust (*Puccinia striiformis f. sp. tritici*) of wheat during grain filling, with a tendency to lower yields. The effects of stripe rust on N yield are most likely associated with reduced N uptake during grain filling [14]. *Blumeria graminis f.sp. tritici* increased nitrogen content from 6.6% to 12.5%, nitrogen accumulation from 1.4% to 6.9%, and nitrogen allocation rate in intercropped wheat leaves from 9.0% to 15.5% at the maximum infection stage [63]. Similarly, *Blumeria graminis f.sp. tritici* inhibited the activity of glutamine synthetase and glutamate synthase, which play a colossal role in plant nitrogen metabolism, as well as the expression of glutamine synthetase in susceptible wheat (Xi'nong 979), which caused inhibition of nitrogen metabolism in grains 20–30 days after anthesis [16]. Thus, a study of the influence of three cropping regimes (wheat monoculture, faba bean monoculture, and wheat/bean intercropping) and four nitrogen levels [N0 (0 kg/ha), N1 (90 kg/ha), N2 (180 kg/ha), and N3 (270 kg/ha)] showed that over two consecutive planting seasons, the severity of wheat powdery mildew and stripe rust increased sharply as higher amounts of nitrogen were applied. For the two planting seasons, powdery mildew increased on average by 77.0–134.1 and 109.4–154.7%, and stripe rust by

37.8–350.2 and 74.4–287.8%, respectively. The incidence and disease index of wheat powdery mildew and stripe rust were highest at the N3 level, followed by N2, N1, and N0 [32]. Regardless of the monocropping or intercropping regime, N application tended to increase the occurrence and severity of powdery mildew and wheat stripe rust, which had the highest incidence and disease index raised to the N3 level (Table) [32]. These results are similar to those of Zhu et al. (2017). With increasing nitrogen application of N1 (112.5 kg hm^{-2}), N2 (225 kg hm^{-2}), and N3 (337.5 kg hm^{-2}), the incidence of wheat powdery mildew disease increased on average from 39.6% to 55.6% and the disease severity index from 92.5% to 217.0%. These indices were higher in monoculture than in the intercropping of wheat and faba beans [63]. Thus, the nitrogen level not only influenced disease occurrence but also decreased the relative efficiency of the intercropping system. The severity of powdery mildew and septoria leaf spot increased with yearly N application, especially early N application [41]. Nitrogen applied earlier resulted in a higher demand for disease control [41]. The highest level of septoria severity in four varieties of durum wheat was recorded for the 150 kg/ha dose, followed by the two doses of 100 and 50 kg/ha. As a result, the addition of nitrogen fertilizer stimulates and amplifies the incidence of this disease. In addition, it has also been observed that direct seeding, being responsible for the preservation of the soil microflora and the sources of inoculum of septoria wilt, is also the main reason for the increase in the disease incidence and severity paired with high doses of nitrogen (150 kg/ha) [7].

Rempelos et al. (2018) suggest that the application of NPK mineral fertilizers reduces the content of phenolic acid and flavonoids in the leaf tissues of wheat and increases the susceptibility of wheat to lodging and powdery mildew. Unlike herbicides, fungicides and growth regulators ensure the reduction of lodging and leaf diseases without affecting the latter [45]. Fertilizer at the dose of N30P30K30 without the other test factors induced an increase in the spread of root rot by an average of 2.7% during the emergence phase of wheat caused by *Alternaria sp*., *Bipolaris sp*., and *Fusarium sp*. [44]. Rogozhnikova et al. (2016) also reported that the application of mineral and new organomineral fertilizers based on chicken manure at the same time reduced the damage caused by root rot and helminthosporiosis on spring barley and had a tendency to increase the development of powdery mildew and leaf rust. A stronger grain infection by fungi of the genera *Alternaria* and *Fusarium* was noticed [47]. This shows that the reasoning for nitrogen fertilization for cereals should take into consideration the nature and the dose to be applied as well as the telluric phytosanitary aspect of the crops.

This problem is more complex in the barley chain than in wheat because it concerns not only diseases but also the quality of malted barley. In malting barley, the starch content is paramount, combined with good phosphorus-potassium nutrition. Increasing nitrogen nutrition reduces its accumulation. Studies have shown that a change in seed quality following an increase in fertilizer concentration decreases the purpose of barley use. The use of higher doses (up to 90 kg/ha) contributed to the increase in yield, maximized the crude protein content of the grain, and reduced the starch and extract content. This grain is not suitable for mashing in terms of protein content but can be used for livestock needs [22].

Wheat agricultural production management strategy

Good control practices include adjusting sowing dates, optimizing sowing rate, improving sowing methods and sowing depth, developing quality seeds and rapidly multiplying seeds of new wheat varieties, treating seeds with combined preparations containing several active substances that solve complex seed protection problems, developing varieties with high yield potential and resistance to biotic and abiotic stresses and with good end-use quality [18, 27, 39]. Yet, under natural conditions, temperatures are constantly changing, and the effect of this on resistance requires further study so that planting strategies can be provided promptly to avoid or mitigate the negative impacts of climate change [23]. In general, it would be important to focus on the transfer of resistance genes or quantitative trait loci not sensitive to temperature or to plant new cereals that have higher heat requirements and a longer reproductive growth period [23, 37].

Thus, the grain yield losses of the Mexicali cultivar of durum wheat in Algeria were -37.5%, -35%, and -7% with early sowing on September 15, October 15, and November 15, respectively. On the other hand, late sowing on November 30 and December 15 increased grain yields by +13% and +27%, respectively [30]. Early sowing in mid-September and October will result in improved wheat yields as it allows wheat plants to benefit from increased rainfall throughout the fall season in 2035–2064. This early sowing will ensure good vegetative development and allow flowering and filling of wheat grains before the spring warming period [30]. In Morocco, early sowing (November 1, 2011 and November 16, 2011) of wheat leads to higher yields compared to late sowing (date of observation: December 1, 2011) of 7.40 to 5.32 t/ha [6]. In addition, a considerable reduction of more than 40% of applied irrigation water can be obtained by optimizing sowing dates in the semi-arid region of Haouz (Morocco) [6]. However, the best sowing dates depend largely on weather conditions and farming regions. The optimal conditions for growing winter wheat in the experiment in the Ulyanovsk region of Russia, on average over 6 years, were formed during sowing from August 30 to September 10 [49]. The highest grain yield (4.8... 5.1 t/ha) of the Marathon variety was noted for bare fallow, for peas it was 1.3... 1.4 times lower (3.7... 3.8 t/ha) [49]. Earlier (August 20) and later (September 20 to October 10) sowing ensured the formation of much lower yields [49]. The maximum content of protein (13.6%) and gluten (31.9%) in the experiment was noted in winter wheat grain during a late sowing period (October 10) for fallow naked, the minimum of September 10 for peas (respectively 12.2 and 28.8%). In the first case, this can be explained by the low planting density: a large feeding area played a positive role in creating high-quality grain of winter wheat. In the second, quality indicators were low due to optimal stem density and high yield [49]. Indeed, early sowing as a rule forms a large vegetative mass, which creates the prerequisites for the most developed autumn shoots to die from damping off, and late sowing does not have time to develop, remaining on the primary roots, winter poorly and grow weakly, which affects their productivity [49].

Using early-flowering winter wheat cultivars shows higher yield gains (26–38%) than early sowing (6–10%), which is able to reverse yield reductions. Adopted early-flowering cultivars successfully advance the onset of anthesis and grain-filling period, which reduces or avoids the risk of exposure to increased drought and heat stress in late spring [60]. Additionally, the near-constant increases in average yields for 2021–2050 and 2051–2080 (up to 39%), using 30% early flowering cultivars, may highlight potential opportunities for improved local yields despite adverse conditions. unfavorable climatic conditions [60].

To achieve food security, farmers depend on quality seeds of varieties appropriate to their needs. However, over the past decades in Russia, the contribution of cereal varietal selection has been estimated at 30–70%, and as climate change intensifies, it will steadily increase [1]. The system of increasing the production of high-quality wheat grains can work effectively only if there is an appropriate economic mechanism to increase the economic interest of participants in agricultural activity. In this regard, it should be noted that in recent years, the development of the grain economy in the Russian Federation has been facilitated by the following state support measures that have boosted grain production: the granting of subsidies for the granting of untied support to agricultural producers in the field of crop production; the provision of subsidies to reimburse part of the costs of agricultural producers to pay interest on loans for the development of agricultural production, and short-term preferential loans [1].

Seed treatment with pesticides is one of the targeted, economical, and environmentally friendly measures to protect plants from diseases and pests. Thus, the initial treatment of wheat seeds with carboxin + thiram resulted in grain yield increases of 9% and 8% in successive years compared to the supplemental control treatment [50]. A single foliar spray after flowering further increased grain yields by up to 15%, demonstrating the potential of this complementary fungicidal approach [50]. Similarly, seed treatment with tebuconazole, triticonazole individually increased yield by 8–9%. When the seeds were treated with disinfectants based on two active ingredients, the yield increased by 14–16% [29].

For editing plant genomes, the researchers used a number of experimental developments, such as zinc finger nuclease (ZFN), transcription activator-like effector nucleases (TALEN), and a nuclease 9 associated with short repeats. regularly spaced palindromics (CRISPR/Cas9): from virtual bioinformatics selection of targets in the wheat genome to obtaining seeds that successfully inherit introduced mutations. For the first time, the CRISPR/Cas9 system was successfully used to edit the TaMLO gene (Mildew resistance locus O) in wheat in 2014, the HKT1 gene (high-affinity potassium transporter gene) in maize in 2014, and HvPM19 (codes for a plasma membrane protein) from barley in 2015 [53]. Now, the number of experimental and methodological publications on genome editing of these cultures using CRISPR/Cas is increasing exponentially every year, and editing efficiency is reaching very high frequencies—from mutations are found in nearly 100% of edited maize and barley plants and reaches, at best, just over 50% for wheat [53]. Similarly, work has also been published aimed at reducing the allergen content of wheat grain by genetic editing of the conserved region of α-gliadin (nRNA) synthesis genes [53].

The first genome-edited wheat plant obtained through the use of CRISPR-Cas9 was reported by Wang et al. (2014). This was achieved in combination with TALEN genome editing technology to eliminate the three sub-genomes of the MLO (Mildew Resistance Locus) gene to confer resistance to powdery mildew in wheat [58]. Similarly, the gene encoding enhanced disease resistance1 (EDR1), a negative factor against powdery mildew defenses, was simultaneously modified using CRISPR/Cas9, generating wheat with improved resistance to powdery mildew [61]. Wang W. et al. (2018) also demonstrated multiplexed gene editing of three wheat genes, TaGW2 (a negative regulator of grain traits), TaLpx-1 (lipoxygenase, which confers resistance to *Fusarium graminearum*) and TaMLO (loss of function, which confers resistance to powdery mildew), using the wheat snRNA U3 promoter [59]. The deoxynivalenol-induced transcription factor TaNFXL1 promotes wheat susceptibility to

Fusarium graminearum by unknown mechanisms. Thus, CRISPR-mediated genome editing of the Fielder cultuvar indicated that TaNFXL1 represses *F. graminearum* resistance [10]. Thus, CRISPR/Cas9 is an important way to improve wheat disease resistance.

The usefulness of these "good prophylactic practices", which aim to prevent the appearance or spread of disease by tilling the soil before sowing and the choice of rotation, to develop resource conservation technologies to improve fertility and soil productivity in a changing climate [23, 27].

Thus, a diversified crop rotation improved the yield of spring wheat by up to 30% in direct seeding and 13% in plowing compared to monoculture. Similarly, on average, the severity of wheat leaf spot disease, mainly caused by *Pyrenophora tritici-repentis*, was 20% lower when wheat was grown every four years (spring wheat-shuttle-barley-pea) compared to wheat monoculture in southwestern Finland [28]. The yield in the summer fallow rotation was 4.31 t/ha, the yield where the predecessor of wheat had been pea, was 4.00 t/ha, and the yield in the gain-grass rotation was 3.94 t/ha for twenty years of experience [52]. Crop rotation reduces yield losses caused by weather extremes for spring (barley and wheat) and winter (oats, wheat, and rye) cereals, providing great benefits, especially under dry conditions. On average, winter and spring cereals are produced more in diversified rotation, producing, respectively, 860 and 390 kg/ha per year, which corresponds to a yield gain of 20 to 25% compared to monoculture [35]. When sowing on fallow land, on average for 2018–2021, the new variety Omskaya 44 (created by the method of intraspecific hybridization) significantly exceeded the standard Duet and the best variety of the forest-steppe zone, Omskaya 38, in terms of yield. The excess protein and gluten content in the grain of the new variety averaged 2.23 and 4.00%, respectively, compared to the norm [5]. Similarly, septoria caused yield losses for both sensitive varieties (Razzak and Karim) and the most tolerant varieties, including Maâli and Salim. The incidence of this disease was also higher in direct sowing for the four genotypes tested compared to conventional. The nitrogen and protein content for the two tolerant genotypes (Maâli and Salim) increased by 20% and 22%, respectively, when applying conventional seeding compared to direct seeding [7].

One of the possible levers of action is to improve the management of nitrogen fertilization, a key factor in controlling and increasing yields. In addition, this fertilization is an important component in the management of some of the most dreaded diseases in wheat-producing regions. Thus, the supply of fertilizers at a dose of 1.5 g/L and especially that of ammonium nitrate significantly reduced the severity of the disease of wheat inoculated with *F. culmorum*, resulting in an improvement in grain yield and of its components [16-18]. As part of the control of wheat powdery mildew *(Blumeria graminis f. sp. tritici*) and stripe rust (*Puccinia striiformis* Westend *f. sp. tritici*) and crop yield increase, nitrogen fertilization with 180 kg/ha was found to be optimal in southwest China [32].

Improve the irrigation system to ensure the water supply of wheat during the critical growth period, which is beneficial to reduce the impacts of the drier climate in tropical and subtropical areas and reducing yield losses of wheat [23, 43]. In addition, regular irrigation can reduce leaf colonization by spores [43].

Under unique spring irrigation conditions in the North China Plain, 90 mm of irrigation at the 4-leaf age of wheat in spring was the optimal time for water use efficiency, and grain yield. The increase in grain number can be attributed to the higher daily water intake and percentage water intake of the L4 throughout the join-anthesis stages compared to the visible 3-leaf (L3) stages, visible 4-leaf stage (L4), visible 5-leaf stage (L5), and visible 6-leaf stage (L6) [4].

More recently, the applications of nanotechnology in the agricultural field most often consist of encapsulating known herbicides, fungicides, or insecticides in synthetic nanocarriers composed of clay, silica, lignin, or natural polymers, in particular alginate, chitosan, and ethylcellulose [27].

To prepare for adaptation to climate change, it is necessary to isolate the effects of each factor for possible impacts on yield, as changes in different factors generally require different coping strategies [31, 62].

First, constant monitoring for the emergence of new plant diseases and improved pest forecasting systems. Climate changes on the planet are of international importance, so it would be expedient to create an international network of observations of the spread of plant diseases and microorganisms in the soil habitat and to ensure a constant exchange of information between countries [31].

The exchange of information at the international level on trade flows as well as on the occurrences and interceptions of harmful organisms is extremely important to compensate for the lack of data from scientific research on the effects of climate change on plant health. It is also essential to share information on the evolution of the distribution of pests and their host ranges, as well as on the adaptive capacity of pests and host plants [27].

Coating urea with secondary nutrients, neem oil, and microorganisms are very effective technique to improve fertilizer use efficiency and wheat production in calcareous soils and reduce nitrogen in the soil and arid environments (Ghafoor et al., 2021). To optimize grain protein accumulation and quality formation, it is essential to manipulate the source-sink relationship by increasing grain N demand and N metabolism activity, resulting in the remobilization of more N [33].

Growing concerns have been expressed by the public about environmental contamination, food safety, and human health issues arising from the heavy use of pesticides in agriculture and food production. Therefore, the application of biopesticides based on strains of *C. rosea*, *T. harzianum*, *P. fluorescens*, and *B. subtilis* will reduce the use of fungicides, as detailed by [15].

From planting crops to harvesting, wheat must be placed after the predecessors of perennial legumes and leguminous crops in the rotation, as well as biological preparations as fertilizers, and replace nano-fertilizers with conventional fertilizers to ensure environmental safety. However, a combination of silicate and nitrogen fertilization can also be used. Because experiments in different countries, including Germany, China, New Jersey, Brazil, Poland, Egypt, Canada, and Iran, have shown that fertilizing soil or treating plants with silicon improves the quantity and quality of wheat yields under different conditions [13]. Applying silicon, applied to the soil as calcium magnesium silicate in the furrow and as potassium silicate applied to the leaves or as soluble sodium metasilicate, can reduce up to 5–80% of the severity of wheat blast caused by *Magnaporthe oryzae*, powdery mildew caused by *Blumeria. graminis f. sp. tritici*, *Fusarium* head blight caused by *Fusarium graminearum*, leaf spot caused by *Bipolaris sorokiniana*, leaf spot caused by *Stagonospora nodorum*, septoria leaf spot caused by *Zymoseptoria tritici*, leaf spot caused by *Oculimacula yallundae*, and tan spots caused by *Pyrenophora tritici-repentis* [13]. The role of Si in wheat-pathogen interactions is linked to its action to modulate the plant's defense against the stressor [13]. Indeed, in wheat, it stimulates the production of glutathione reductase, phenolic compounds (flavonoids), phytoalexins, ligninthioglycolic acid, and H_2O_2, which leads to an increase in the incubation period and a reduction in the colonization of host cells by the pathogen [13].

Conclusion

In conclusion, the evidence revealed in this review indicates that climate change will in many cases lead to an increase in the various diseases attacking wheat. However, these recent climate changes are already forcing changes in plant protection protocols. To develop an effective agricultural management strategy, future research should be based on the study of the interactions among crops, pests, pathogens and farming system under climate change, taking into account all parameters such as temperature increase and CO2, extreme precipitation, etc.

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References

1. Altukhov A. I., Zavalin A. A., Milaschenko N. Z., Trushkin S. V. The problem of improving wheat quality in the country requires a complex solution. *Vestnik of Kursk State Agricultural Academy*, 2020, no. 2, pp. 32-39.
2. Asseng S., Ewert F., Martre P., et al. Rising temperatures reduce global wheat production. *Nature Clim Change*, 2015, vol. 5 no. 2, pp. 143–147. https://doi.org/10.1038/nclimate2470
3. Bajwa A. A., Farooq M., Al-Sadi A.M., Nawaz A., Jabran K., Siddique K.H.M. Impact of climate change on biology and management of wheat pests. *Crop Protection*, 2020, vol. 137, no. 105304. https://doi.org/10.1016/j.cropro.2020.105304
4. Bao, X., Liu, X., Hou, X. *et al.* Single irrigation at the four-leaf stage in the spring optimizes winter wheat water consumption characteristics and water use efficiency. *Sci Rep*, 2022, vol. 12, pp. 14257. https://doi.org/10.1038/s41598-022-18446-8
5. Belan I. A., Rosseeva L. P., Grigoriev Yu. P., Pakhotina I. V. High-quality variety of soft spring wheat Omskaya 44 for the conditions of Western Siberia and Omsk region. *Agricultural Science Euro-North-East*, 2022, vol. 23, no. 2, pp. 174-183. https://doi.org/10.30766/2072-9081.2022.23.2.174-183
6. Belaqziz S., Khabba S., Kharrou MH., Bouras EH., Er-Raki S., Chehbouni A. Optimizing the Sowing Date to Improve Water Management and Wheat Yield in a Large Irrigation Scheme, through a Remote Sensing and an Evolution Strategy-Based Approach. *Remote Sensing*, 2021, vol.13, no. 18, 3789. https://doi.org/10.3390/rs13183789
7. Ben Omrane M. *Study of nitrogen absorption and remobilization mechanisms in order to characterize the efficiency of nitrogen use in durum wheat under biotic stress (septoria). Dissertation (Master of science): CIHEAM-IAMM, Montpellier (France), 2020 p. 68 (Master of Science: Professional, num.969).* http://www.iamm.ciheam.org/ress_doc/opac_css/index.php?lvl=notice_display&id=42265
8. Bencze S., Vida G., Balla K., Varga-László E., Veisz O. Response of wheat fungal diseases to elevated atmospheric CO_2 Level. *Cereal Res Commun*, 2013, vol. 41, pp. 1–11. https://doi.org/10.1556/CRC.2013.0021
9. Blandino M., Badeck F.W., Giordano D., Marti A., Rizza F., Scarpino V., & Vaccino, P. Elevated CO_2 Impact on Common Wheat (*Triticum aestivum* L.)

Yield, Wholemeal Quality, and Sanitary Risk. *Journal of agricultural and food chemistry*, 2020, vol. 68(39), pp. 10574–10585. https://doi.org/10.1021/acs.jafc.0c02975

10. Brauer E. K., Balcerzak M., Rocheleau H., Leung W., Schernthaner J., Subramaniam R., Ouellet T. Genome Editing of a Deoxynivalenol-Induced Transcription Factor Confers Resistance to *Fusarium graminearum* in Wheat. *Molecular plant-microbe interactions: MPMI*, 2020, vol. *33*, no. 3, pp. 553–560. https://doi.org/10.1094/MPMI-11-19-0332-R
11. Bryant R.R.M., Mcgrann G.R.D., Mitchell A.R., Schoonbeek H., Boyd L.A., Uauy C., Dorling S., Ridout C.J. A change in temperature modulates defence to yellow (stripe) rust in wheat line UC1041 independently of resistance gene Yr36. *BMC. Plant Biol*, 2014, vol. 14, no.10. https://doi.org/10.1186/1471-2229-14-10
12. Chekali S., Gargouri S., Berraies S., Gharbi M.S., Nicol M.J., Nasraoui B. Impact of *Fusarium* foot and root rot on yield of cereals in Tunisia. *Tunisian Journal of Plant Protection*, 2013, vol. 8, no. 2, pp. 75-86.
13. Dallagnol L.J., Ramos A.E. R., Dorneles K.d.R. Silicon use in the integrated disease management of wheat: current knowledge. in (ed.), current trends in wheat research. *IntechOpen*, 2020 https://doi.org/10.5772/intechopen.95285
14. Devadas R., Simpfendorfer S., Backhouse D., Lamb D.W. Effect of stripe rust on the yield response of wheat to nitrogen. *Crop J.*, 2014, vol. 2, pp. 201–206. https://doi.org/10.1016/j.cj.2014.05.002
15. Diakite S., Pakina E., Zargar M., Aldaibe A. A.D., Denis P., Gregory L., Behzad A. Yield losses of cereal crops by *Fusarium* Link: A review on the perspective of biological control practices. *Res. Crop*, 2022, vol. 23, no. 2, pp. 418-436. https://doi.org/10.31830/2348-7542.2022.057
16. Eddine B.S., El Yousfi B., Douira A. Interaction of nitrogen fertilizers with wheat growth stage and foliar treatment with urea effects on WCR induced by *Fusarium culmorum*. *Plant Archives*, 2019, vol. 19, no.2, pp. 2829-2835.
17. Eddine B.S., El Yousfi B., Douira A. Effects of nitrogen forms and rates on *Fusarium culmorum* growth, fitness, aggressiveness and wheat, barley and triticale resistance to crown rot disease. *Plant Cell Biotechnology and Molecular Biology*, 2020, vol. 21, pp. 107-129.
18. Eddine B.S., Douira A., El Yousfi B. Effect of nitrogenous fertilizers on wheat and barley yield under biotic stress due to dry crown rot induced by *Fusarium culmorum*. *Moroccan Journal of Agricultural Sciences*, 2022, vol. 10(1), pp. 17-30. (In French)
19. Erenstein O., Jaleta M., Mottaleb K.A., Sonder K., Donovan J., Braun HJ. Global trends in wheat production, consumption and trade. In: Reynolds,

M.P., Braun, HJ. (eds) wheat improvement. *Springer Cham*, 2022. https://doi.org/10.1007/978-3-030-90673-3_4
20. FAO. Quarterly Global Report: Crop Prospects and Food Situation. *FAO, 2018*. http://www.fao.org/publications
21. Gao H., Niu J., Liu W., Zhang D., Li S. Effect of wheat powdery mildew on grain nitrogen metabolism. *The Journal of Agricultural Science*, 2022, vol. 159, no. 1-2, pp. 128-138. https://doi.org/10.1017/S0021859621000307
22. Gavrilova A.Yu., Konova A.M., Samsonova N.E. Influence of doses and combinations of mineral fertilizers on formation of productivity and quality of malting barley grain in the Central Non-Chernozem Region, *Agrochemicals*, 2020, no. 9, pp. 24–31. https://doi.org/10.31857/S0002188120090069
23. Geng X., Wang F., Ren W., Hao Z. Climate change impacts on winter wheat yield in Northern China. *Advances in Meteorology*, 2019, vol. 2019, pp. 1–12. https://doi.org/10.1155/2019/2767018
24. Ghafoor I., Habib-Ur-Rahman M., Ali M., Afzal M., Ahmed W., Gaiser T., Ghaffar A. Slow-release nitrogen fertilizers enhance growth, yield, NUE in wheat crop and reduce nitrogen losses under an arid environment. *Environ Sci Pollut Res*, 2021, vol. 28, no. 32, pp. 43528–43543. https://doi.org/10.1007/s11356-021-13700-4
25. Guo J., Jia Y., Chen H., Zhang L., Yang J., Zhang J., Hu X., Ye X., Li Y., Zhou Y. Growth, photosynthesis, and nutrient uptake in wheat are affected by differences in nitrogen levels and forms and potassium supply. *Scientific reports*, 2019, vol. 9(1), no. 1248. https://doi.org/10.1038/s41598-018-37838-3
26. Gupta N., Debnath S., Sharma S., Sharma P., Purohit J. Role of nutrients in controlling the plant diseases in sustainable agriculture. In: Meena, V., Mishra, P., Bisht, J., Pattanayak, A. (eds) *Agriculturally important microbes for sustainable agriculture*. Springer, Singapore, 2017. https://doi.org/10.1007/978-981-10-5343-6_8
27. IPPC Secretariat. Scientific review of the impact of climate change on plant pests – A globa challenge to prevent and mitigate plant pest risks in agriculture, forestry and ecosystems. Rome. *FAO on behalf of the IPPC Secretariat, 2021*. https://doi.org/10.4060/cb4769en
28. Jalli M., Huusela E., Jalli H., Kauppi K., Niemi M., Himanen S., Jauhiainen L. Effects of Crop Rotation on Spring Wheat Yield and Pest Occurrence in Different Tillage Systems: A Multi-Year Experiment in Finnish Growing Conditions. *Front. Sustain. Food Syst.*, 2021, vol. 5, pp. 647335. https://doi.org/10.3389/fsufs.2021.647335
29. Kekalo A.Yu., Zargaryan N.Yu., Filippov A.S., Nemchenko V.V. Efficiency of application of fungicides for spring wheat protection against root rots. *Siberi-*

an Herald of Agricultural Science, 2019, vol. 49, no. 3, pp. 24-30. https://doi.org/10.26898/0370-8799-2019-3-3

30. Kourat T., Smadhi D., Madani A. Modeling the Impact of Future Climate Change Impacts on Rainfed Durum Wheat Production in Algeria, *Climate*, 2022, vol.10, no. 4, 50. https://doi.org/10.3390/cli10040050
31. Levitin M.M. Microorganisms and global climate change. *Sel'skokhozyaistvennaya biologiya* [Agricultural Biology], 2015, vol. 50, no. 5, pp. 641-647. https://doi.org/10.15389/agrobiology.2015.5.641rus
32. Luo C., Ma L., Zhu J., Guo Z., Dong K., Dong Y. Effects of nitrogen and intercropping on the occurrence of wheat powdery mildew and stripe rust and the relationship with crop yield. *Front. Plant Sci.,* 2021, vol. 12, no. 637393. d https://doi.org/10.3389/fpls.2021.637393
33. Lyu X., Liu Y., Li N., Ku L., Hou Y., Wen X. Foliar applications of various nitrogen (N) forms to winter wheat affect grain protein accumulation and quality via N metabolism and remobilization. *The Crop Journal*. 2022, vol. 10, pp. 1165–1177. https://doi.org/10.1016/j.cj.2021.10.009
34. MAPM. Moroccan agriculture in figures 2017, 2018 edition. *Ministry of Agriculture and Maritime Fisheries (MAPM)*, 2017. http://www.agriculture.gov.ma/sites/default/files/AgricultureEnChiffre2017VAVF.pdf
35. Marini L., St-Martin A., Vico G., Baldoni G., Berti A., Blecharczyk A., et al. Crop rotations sustain cereal yields under a changing climate. *Environ. Res. Lett.*, 2020, vol. 15, no. 12, pp. 124011. https://doi.org/10.1088/1748-9326/abc651
36. Matić S., Cucu M.A., Garibaldi A., Gullino M.L. Combined effect of co_2 and temperature on wheat powdery mildew development. *The plant pathology journal*, 2018, vo.l 34, no. 4, pp. 316–326. https://doi.org/10.5423/PPJ.OA.11.2017.0226
37. Miedaner T., Juroszek P. Climate change will influence disease resistance breeding in wheat in Northwestern Europe. *Theor Appl Genet,* 2021, vo. 134, no. 6, pp. 1771–1785. https://doi.org/10.1007/s00122-021-03807-0
38. Navarro C. E., Lam S.K., Trębicki P. Elevated carbon dioxide and nitrogen impact wheat and its aphid pest. *Frontiers in plant science*, 2020, vol. 11, no. 605337. https://doi.org/10.3389/fpls.2020.605337
39. Nazari M., Mirgol B., Salehi H. climate change impact assessment and adaptation strategies for rainfed wheat in contrasting climatic regions of Iran. *Front. Agron*, 2021, vol. 3, no. 806146. https://doi.org/10.3389/fagro.2021.806146
40. Nuttall J., Brady S., Brand J., O'Leary G., Fitzgerald GJ. Heat waves and wheat growth under a future climate. *In The 16th Australian Agronomy Con-*

ference: Climate Change, pp. 14-18. http://www.regional.org.au/au/asa/2012/climate-change/8085_nuttalljg.htm
41. Olesen J., Jørgensen L., Petersen J., Mortensen J. Effects of rate and timing of nitrogen fertilizer on disease control by fungicides in winter wheat. 1. Grain yield and foliar disease control. *The Journal of Agricultural Science,* 2003, vol. 140, no. 1, pp. 1-13. https://doi.org/10.1017/S0021859602002885
42. Park, R.F., Golegaonkar, P.G., Derevnina, L., Sandhu, K. S., Karaoglu, H., Elmansour, H.M., Dracatos, P.M., Singh,D. Leaf rust of cultivated barley: pathology and control. *Annual review of phytopathology*, 2015, vol. 53(1), pp. 565–589. https://doi.org/10.1146/annurev-phyto-080614-120324
43. Prank M., Kenaley SC., Bergstrom G.C., Acevedo M., Mahowald N.M. Climate change impacts the spread potential of wheat stem rust, a significant crop disease. *Environmental Research Letters*, 2019, vol. 14, no. 12, p. 124053. https://doi.org/10.1088/1748-9326/ab57de
44. Razina A.A., Dyatlova O.G. Reduction of root rot harmful effect by agrobackground and seed treatment. *Siberian Herald of Agricultural Science*. 2015, no. 5, pp. 19-24.
45. Rempelos L., Almuayrifi A.M., Baranski M., Tetard-Jones C., Eyre M., Shotton P., Cakmak I., Ozturk L., Cooper J., Volakakis N., Schmidt C., Sufar E., Wang J., Wilkinson A., Rosa E.A.S., Zhao B., Rose T.J., Leifert C., Bilsborrow P. Effects of agronomic management and climate on leaf phenolic profiles, disease severity, and grain yield in organic and conventional wheat production systems. *Journal of Agricultural and Food Chemistry,* 2018, vol. *66* (40), pp. 10369-10379. https://doi.org/10.1021/acs.jafc.8b02626
46. Rettie F.M., Gayler S., Tobias K.D., Weber T., Tesfaye K., Streck T. Climate change impact on wheat and maize growth in Ethiopia: A multi-model uncertainty analysis. *PloS one*, 2022, vol. 17(1), no. e0262951. https://doi.org/10.1371/journal.pone.0262951
47. Rogojnikova E.S., Shpanev A.M., Fesenko M.A. Influence of fertilizers on the damage of spring barley by diseases in the IV agro-climatic zone Leningrad region. *Vestnik zashchityrasteniy*, 2016 vol. 4, no. 90, pp. 56–61.
48. Różewicz M., Wyzińska M., Grabiński J. The Most important fungal diseases of cereals—problems and possible solutions. *Agronomy*, 2021, vol. 11, no. 4, pp. 714. https://doi.org/10.3390/agronomy11040714
49. Sharipova R. B., Khakimov R. A., Khakimova N. V. Influence of precurses and sowing date on overwintering and winter wheat productivity under changing regional conditions. *Vestnik of the Kazan State Agrarian University*, 2020, vol. 15, no. 2, pp. 66-71. https://doi.org/10.12737/2073-0462-2020-66-71

50. Sharma-Poudyal D., Sharma R.C., Duveiller E. Control of *Helminthosporium* leaf blight of spring wheat using seed treatments and single foliar spray in Indo Gangetic Plains of Nepal. *Crop Protect*, 2016, vol. 88, pp. 161–166. https://doi.org/10.1016/j.cropro.2016.06.017
51. Shivay Y.S., Pooniya V., Prasad R., Pal M., Bansal R. Sulphur-coated urea as a source of sulphur and an enhanced efficiency of nitrogen fertilizer for spring wheat. *Cereal Res Commun*, 2016, vol. 44, no. 3, pp. 513–523. https://doi.org/10.1556/0806.44.2016.002
52. Solovichenko V.D., Nikitin V.V., Karabutov A.P., Navolneva E.V. The impact of crop rotation, methods of tillage and fertilizers on the yield and economic performance of winter wheat. *Agrarian science*, 2018, no. 5, pp. 46-49.
53. Strygina K.V., Khlestkina E.K. Wheat, barley and maize genes editing using the CRISPR/Cas system. *Plant Biotechnology and Breeding,* 2020, vol. 3, no. 1, pp. 46-56. https://doi.org/10.30901/2658-6266-2020-1-o2
54. Tadesse W., Bishaw Z., Assefa S. Wheat production and breeding in Sub-Saharan Africa: Challenges and opportunities in the face of climate change, *International Journal of Climate Change Strategies and Management*, 2019, vol. 11, no. 5, pp. 696-715. https://doi.org/10.1108/IJCCSM-02-2018-0015
55. Tuktarova N.G. impact of current climate change trends on the state of winter cereal crops. *Perm Agrarian Journal*, 2019, vol. 25, no. 1, pp. 80–86.
56. Váry Z., Mullins E., McElwain J.C., Doohan F.M. The severity of wheat diseases increases when plants and pathogens are acclimatized to elevated carbon dioxide. *Glob Chang Biol*, 2015, vol. 21, no. 7, pp. 2661-2669. https://doi.org/10.1111/gcb.12899
57. Wang B.X., Hof A.R., Ma C.S. Impacts of climate change on crop production, pests and pathogens of wheat and rice. *Frontiers of Agricultural Science and Engineering*, 2022, vol. 9, no. 1, pp. 4-18. https://doi.org/10.15302/J-FASE-2021432
58. Wang Y., Cheng X., Shan Q., Zhang Y., Liu J., Gao C., Qiu J.L. Simultaneous editing of three homoeoalleles in hexaploid bread wheat confers heritable resistance to powdery mildew. *Nature Biotechnology*, 2014, vol. 32, no. 9, pp. 947-951. https://doi.org/10.1038/nbt.2969
59. Wang W., Pan Q., He F., Akhunova A., Chao S., Trick H., Akhunov E. Transgenerational CRISPR-Cas9 Activity Facilitates Multiplex Gene Editing in Allopolyploid Wheat. *CRISPR J.*, 2018, vol.1, no. 1, pp. 65–74. https://doi.org/10.1089/crispr.2017.0010
60. Yang C., Fraga H., van Ieperen W. et al. Effects of climate change and adaptation options on winter wheat yield under rainfed Mediterranean conditions in

southern Portugal. *Climatic Change*, 2019, vol. 154, no. 1, pp. 159–178. https://doi.org/10.1007/s10584-019-02419-4

61. Zhang Y., Bai Y., Wu G., Zou S., Chen Y., Gao C., Tang D. Simultaneous modification of three homoeologs of TaEDR1 by genome editing enhances powdery mildew resistance in wheat. *Plant Journal*, 2017, vol. 91, no. 4, pp. 714-724. https://doi.org/10.1111/tpj.13599
62. Zhao C., Liu B., Piao S., Wang X., Lobell D.B., Huang Y., Huang M., Yao Y., Bassu S., Ciais P., Durand J.L., Elliott J., Ewert F., Janssens I.A., Li T., Lin E., Liu Q., Martre P., Müller C., Peng S., Peñuelas J., Ruane A.C., Wallach D., Wang T., Wu D., Liu Z., Zhu Y., Zhu Z., Asseng S. Temperature increase reduces global yields of major crops in four independent estimates. *Proceedings of the National Academy of Sciences of the United States of America*, 2017, vol. 114, no. 35, pp. 9326–9331. https://doi.org/10.1073/pnas.1701762114
63. Zhu J.H., Dong Y., Xiao J.X., Zhen Y., Tang L. Effects of N application on wheat powdery mildew occurrence, nitrogen accumulation and allocation in intercropping system. *Ying yong sheng tai xue bao = The journal of applied ecology*, 2017, vol. 28, no. 12, pp. 3985–3993. https://doi.org/10.13287/j.1001-9332.201712.029

Список литературы

1. Алтухов А. И., Завалин А. А., Милащенко Н. З., Трушкин С. В. Проблема повышения качества пшеницы в стране требует комплексного решения // Вестник Курской государственной сельскохозяйственной академии. 2020. № 2. С. 32-39.
2. Asseng S., Ewert F., Martre P., et al. Rising temperatures reduce global wheat production // Nature Clim Change, 2015, vol. 5 no. 2, pp. 143–147. https://doi.org/10.1038/nclimate2470
3. Bajwa A. A., Farooq M., Al-Sadi A.M., Nawaz A., Jabran K., Siddique K.H.M. Impact of climate change on biology and management of wheat pests // Crop Protection, 2020, vol. 137, 105304. https://doi.org/10.1016/j.cropro.2020.105304
4. Bao, X., Liu, X., Hou, X. *et al.* Single irrigation at the four-leaf stage in the spring optimizes winter wheat water consumption characteristics and water use efficiency // Sci Rep, 2022, vol. 12, 14257. https://doi.org/10.1038/s41598-022-18446-8
5. Белан И. А., Россеева Л. П., Григорьев Ю. П., Пахотина И. В. Высококачественный сорт пшеницы мягкой яровой Омская 44 для условий Западной Сибири и Омской области // Аграрная наука Евро-Северо-Востока, 2022. Т. 23, №. 2. С. 174-183. https://doi.org/10.30766/2072-9081.2022.23.2.174-183

6. Belaqziz S., Khabba S., Kharrou MH., Bouras EH., Er-Raki S., Chehbouni A. Optimizing the Sowing Date to Improve Water Management and Wheat Yield in a Large Irrigation Scheme, through a Remote Sensing and an Evolution Strategy-Based Approach // *Remote Sensing*, 2021, vol. 13, no. 18, 3789. https://doi.org/10.3390/rs13183789
7. Ben Omrane M. *Etude de mécanismes d'absorption et de remobilisation de l'azote afin de parvenir à la caractérisation de l'efficience de l'utilisation de l'azote chez le blé dur sous un stress biotique (la septoriose) // Mémoire (Master of science): CIHEAM-IAMM, Montpellier (France), 2020, pp. 68. (Master of Science: Professionnel, n. 969).* http://www.iamm.ciheam.org/ress_doc/opac_css/index.php?lvl=notice_display&id=42265
8. Bencze S., Vida G., Balla K., Varga-László E., Veisz O. Response of wheat fungal diseases to elevated atmospheric CO_2 Level // Cereal Res Commun, 2013, vol. 41, pp. 1–11. https://doi.org/10.1556/CRC.2013.0021
9. Blandino M., Badeck F.W., Giordano D., Marti A., Rizza F., Scarpino V., & Vaccino, P. Elevated CO_2 Impact on Common Wheat (*Triticum aestivum* L.) Yield, Wholemeal Quality, and Sanitary Risk // Journal of agricultural and food chemistry, 2020, vol. 68(39), pp. 10574–10585. https://doi.org/10.1021/acs.jafc.0c02975
10. Brauer E. K., Balcerzak M., Rocheleau H., Leung W., Schernthaner J., Subramaniam R., Ouellet T. Genome Editing of a Deoxynivalenol-Induced Transcription Factor Confers Resistance to *Fusarium graminearum* in Wheat // Molecular plant-microbe interactions: MPMI, 2020, vol. *33*, no. 3, pp. 553–560. https://doi.org/10.1094/MPMI-11-19-0332-R
11. Bryant R.R.M., Mcgrann G.R.D., Mitchell A.R., Schoonbeek H., Boyd L.A., Uauy C., Dorling S., Ridout C.J. A change in temperature modulates defence to yellow (stripe) rust in wheat line UC1041 independently of resistance gene Yr36. BMC // Plant Biol, 2014, vol.14, no.10. https://doi.org/10.1186/1471-2229-14-10
12. Chekali S., Gargouri S., Berraies S., Gharbi M.S., Nicol M.J., Nasraoui B. Impact of *Fusarium* foot and root rot on yield of cereals in Tunisia // Tunisian Journal of Plant Protection, 2013, vol. 8, no. 2, pp. 75-86.
13. Dallagnol L.J., Ramos A.E. R., Dorneles K.d.R. Silicon use in the integrated disease management of wheat: current knowledge. in (ed.), current trends in wheat research // IntechOpen, 2020 https://doi.org/10.5772/intechopen.95285
14. Devadas R., Simpfendorfer S., Backhouse D., Lamb D.W. Effect of stripe rust on the yield response of wheat to nitrogen // Crop J., 2014, vol. 2, pp. 201–206. https://doi.org/10.1016/j.cj.2014.05.002

15. Diakite S., Pakina E., Zargar M., Aldaibe A. A.D., Denis P., Gregory L., Behzad A. Yield losses of cereal crops by *Fusarium* Link: A review on the perspective of biological control practices // Res. Crop, 2022, vol. 23, no. 2, pp. 418-436. https://doi.org/10.31830/2348-7542.2022.057
16. Eddine B.S., El Yousfi B., Douira A. Interaction of nitrogen fertilizers with wheat growth stage and foliar treatment with urea effects on WCR induced by *Fusarium culmorum* // Plant Archives, 2019, vol. 19, no.2, pp. 2829-2835.
17. Eddine B.S., El Yousfi B., Douira A. Effects of nitrogen forms and rates on *Fusarium culmorum* growth, fitness, aggressiveness and wheat, barley and triticale resistance to crown rot disease // Plant Cell Biotechnology and Molecular Biology, 2020, vol. 21, pp. 107-129.
18. Eddine B.S., Douira A., El Yousfi B. Effets des engrais azotés sur le rendement du blé et de l'orge sous stress biotique dû à la pourriture sèche du collet induite par le *Fusarium culmorum* // Moroccan Journal of Agricultural Sciences, 2022, vol. 10(1) pp. 17-30.
19. Erenstein O., Jaleta M., Mottaleb K.A., Sonder K., Donovan J., Braun HJ. Global trends in wheat production, consumption and trade. In: Reynolds, M.P., Braun, HJ. (eds) wheat improvement, Springer Cham, 2022. https://doi.org/10.1007/978-3-030-90673-3_4
20. FAO. Quarterly Global Report: Crop Prospects and Food Situation. *FAO, 2018*. http://www.fao.org/publications
21. Gao H., Niu J., Liu W., Zhang D., Li S. Effect of wheat powdery mildew on grain nitrogen metabolism // The Journal of Agricultural Science, 2022, vol. 159, no. 1-2, pp. 128-138. https://doi.org/10.1017/S0021859621000307
22. Гаврилова А.Ю., Конова А.М., Самсонова Н. Е. Влияние доз и сочетаний минеральных удобрений на формирование урожайности и качества зерна пивоваренного ячменя в центральном нечерноземье // Агрохимия. 2020. № 9. С. 24–31. https://doi.org/10.31857/S0002188120090069
23. Geng X., Wang F., Ren W., Hao Z. Climate change impacts on winter wheat yield in Northern China // Advances in Meteorology, 2019, vol. 2019, pp. 1–12. https://doi.org/10.1155/2019/2767018
24. Ghafoor I., Habib-Ur-Rahman M., Ali M., Afzal M., Ahmed W., Gaiser T., Ghaffar A. Slow-release nitrogen fertilizers enhance growth, yield, NUE in wheat crop and reduce nitrogen losses under an arid environment // Environ Sci Pollut Res, 2021, vol. 28, no. 32, pp. 43528–43543. https://doi.org/10.1007/s11356-021-13700-4
25. Guo J., Jia Y., Chen H., Zhang L., Yang J., Zhang J., Hu X., Ye X., Li Y., Zhou Y. Growth, photosynthesis, and nutrient uptake in wheat are affected by differences

in nitrogen levels and forms and potassium supply // Scientific reports, 2019, vol. 9(1), no. 1248. https://doi.org/10.1038/s41598-018-37838-3

26. Gupta N., Debnath S., Sharma S., Sharma P., Purohit J. Role of nutrients in controlling the plant diseases in sustainable agriculture. In: Meena, V., Mishra, P., Bisht, J., Pattanayak, A. (eds) Agriculturally important microbes for sustainable agriculture. Springer, Singapore, 2017. https://doi.org/10.1007/978-981-10-5343-6_8
27. IPPC Secretariat. Scientific review of the impact of climate change on plant pests – A globa challenge to prevent and mitigate plant pest risks in agriculture, forestry and ecosystems. Rome. FAO on behalf of the IPPC Secretariat, 2021. https://doi.org/10.4060/cb4769en
28. Jalli M., Huusela E., Jalli H., Kauppi K., Niemi M., Himanen S., Jauhiainen L. Effects of Crop Rotation on Spring Wheat Yield and Pest Occurrence in Different Tillage Systems: A Multi-Year Experiment in Finnish Growing Conditions // Front. Sustain. Food Syst., 2021, vol. 5, pp. 647335. https://doi.org/10.3389/fsufs.2021.647335
29. Кекало А.Ю., Заргарян Н.Ю., Филиппов А.С., Немченко В.В. Эффективность применения фунгицидов для защиты яровой пшеницы от корневых гнилей // Сибирский вестник сельскохозяйственной науки. 2019. Т. 49, № 3. С. 24-30. https://doi.org/10.26898/0370-8799-2019-3-3
30. Kourat T., Smadhi D., Madani A. Modeling the Impact of Future Climate Change Impacts on Rainfed Durum Wheat Production in Algeria // *Climate,* 2022, vol.10, no. 4, 50. https://doi.org/10.3390/cli10040050
31. Левитин М.М. Микроорганизмы в условиях глобального изменения климата // Сельскохозяйственная биология. 2015. Т. 50, №. 5. С. 641-647. https://doi.org/10.15389/agrobiology.2015.5.641rus
32. Luo C., Ma L., Zhu J., Guo Z., Dong K., Dong Y. Effects of nitrogen and intercropping on the occurrence of wheat powdery mildew and stripe rust and the relationship with crop yield // Front. Plant Sci., 2021, vol. 12, no. 637393. d https://doi.org/10.3389/fpls.2021.637393
33. Lyu X., Liu Y., Li N., Ku L., Hou Y., Wen X. Foliar applications of various nitrogen (N) forms to winter wheat affect grain protein accumulation and quality via N metabolism and remobilization // The Crop Journal. 2022, vol. 10, pp. 1165–1177. https://doi.org/10.1016/j.cj.2021.10.009
34. MAPM. L’agriculture marocaine en chiffres 2017, édition 2018 // Ministère de l’Agriculture et de la Pêche Maritime (MAPM), 2017. http://www.agriculture.gov.ma/sites/default/files/AgricultureEnChiffre2017VAVF.pdf
35. Marini L., St-Martin A., Vico G., Baldoni G., Berti A., Blecharczyk A., et al. Crop rotations sustain cereal yields under a changing climate // Environ. Res.

Lett., 2020, vol. 15, no. 12, pp. 124011. https://doi.org/10.1088/1748-9326/abc651
36. Matić S., Cucu M.A., Garibaldi A., Gullino M.L. Combined effect of co_2 and temperature on wheat powdery mildew development // The plant pathology journal, 2018, vo.l 34, no. 4, pp. 316–326. https://doi.org/10.5423/PPJ.OA.11.2017.0226
37. Miedaner T., Juroszek P. Climate change will influence disease resistance breeding in wheat in Northwestern Europe // Theor Appl Genet, 2021, vo. 134, no. 6, pp. 1771–1785. https://doi.org/10.1007/s00122-021-03807-0
38. Navarro C. E., Lam S.K., Trębicki P. Elevated carbon dioxide and nitrogen impact wheat and its aphid pest // Frontiers in plant science, 2020, vol. 11, no. 605337. https://doi.org/10.3389/fpls.2020.605337
39. Nazari M., Mirgol B., Salehi H. climate change impact assessment and adaptation strategies for rainfed wheat in contrasting climatic regions of Iran // Front. Agron, 2021, vol. 3, no. 806146. https://doi.org/10.3389/fagro.2021.806146
40. Nuttall J., Brady S., Brand J., O'Leary G., Fitzgerald GJ. Heat waves and wheat growth under a future climate. In The 16th Australian Agronomy Conference: Climate Change, pp. 14-18. http://www.regional.org.au/au/asa/2012/climate-change/8085_nuttalljg.htm
41. Olesen J., Jørgensen L., Petersen J., Mortensen J. Effects of rate and timing of nitrogen fertilizer on disease control by fungicides in winter wheat. 1. Grain yield and foliar disease control // The Journal of Agricultural Science, 2003, vol. 140, no. 1, pp. 1-13. https://doi.org/10.1017/S0021859602002885
42. Park, R.F., Golegaonkar, P.G., Derevnina, L., Sandhu, K. S., Karaoglu, H., Elmansour, H.M., Dracatos, P.M., Singh,D. Leaf rust of cultivated barley: pathology and control // Annual review of phytopathology, 2015, vol. 53(1), pp. 565–589. https://doi.org/10.1146/annurev-phyto-080614-120324
43. Prank M., Kenaley SC., Bergstrom G.C., Acevedo M., Mahowald N.M. Climate change impacts the spread potential of wheat stem rust, a significant crop disease // Environmental Research Letters, 2019, vol. 14, no. 12, p. 124053. https://doi.org/10.1088/1748-9326/ab57de
44. Разина А.А., Дятлова О.Г. Влияние агрофона и протравливания семян яровой пшеницы на снижение вредоносности корневой гнили // Сибирский Вестник Сельскохозяйственной Науки. 2015. № 5. С. 19-24.
45. Rempelos L., Almuayrifi A.M., Baranski M., Tetard-Jones C., Eyre M., Shotton P., Cakmak I., Ozturk L., Cooper J., Volakakis N., Schmidt C., Sufar E., Wang J., Wilkinson A., Rosa E.A.S., Zhao B., Rose T.J., Leifert C., Bilsborrow P. Effects of agronomic management and climate on leaf phenolic profiles, disease

severity, and grain yield in organic and conventional wheat production systems // *Journal of Agricultural and Food Chemistry,* 2018, vol. *66* (40), pp. 10369-10379. https://doi.org/10.1021/acs.jafc.8b02626

46. Rettie F.M., Gayler S., Tobias K.D., Weber T., Tesfaye K., Streck T. Climate change impact on wheat and maize growth in Ethiopia: A multi-model uncertainty analysis // PloS one, 2022, vol. 17(1), no. e0262951. https://doi.org/10.1371/journal.pone.0262951
47. Рогожникова Е.С., Шпанев А.М., Фесенко М.А. Влияние удобрений на поражение ярового ячменя болезнями в IV агроклиматической зоне Ленинградской области // Вестн. защиты раст. 2016. Т. 4, № 90. С. 56–61.
48. Różewicz M., Wyzińska M., Grabiński J. The Most important fungal diseases of cereals-problems and possible solutions // *Agronomy*, 2021, vol. 11, no. 4, pp. 714. https://doi.org/10.3390/agronomy11040714
49. Шарипова Р. Б., Хакимов Р. А., Хакимова Н. В. Влияние предшественников и сроков сева на перезимовку и урожайность озимой пшеницы в изменяющихся условиях регионального климата // Вестник Казанского государственного аграрного университета. 2020. Т. 15. № 2. С. 66-71. https://doi.org/10.12737/2073-0462-2020-66-71
50. Sharma-Poudyal D., Sharma R.C., Duveiller E. Control of *Helminthosporium* leaf blight of spring wheat using seed treatments and single foliar spray in Indo-Gangetic Plains of Nepal // Crop Protect, 2016, vol. 88, pp. 161–166. https://doi.org/10.1016/j.cropro.2016.06.017
51. Shivay Y.S., Pooniya V., Prasad R., Pal M., Bansal R. Sulphur-coated urea as a source of sulphur and an enhanced efficiency of nitrogen fertilizer for spring wheat // Cereal Res Commun, 2016, vol. 44, no. 3, pp. 513–523. https://doi.org/10.1556/0806.44.2016.002
52. Соловиченко В.Д., Никитин В.В., Карабутов А.П., Навольнева Е.В. Влияние севооборотов, способов обработки почв и удобрений на урожайность и экономические показатели производства пшеницы озимой // Аграрная наука. 2018. №5. С. 46-49.
53. Стрыгина К.В., Хлесткина Е.К. Редактирование генов пшеницы, ячменя и кукурузы с использованием системы CRISPR/Cas // Биотехнология и селекция растений. 2020. Т. 3, № 1. С. 46-56. https://doi.org/10.30901/2658-6266-2020-1-o2
54. Tadesse W., Bishaw Z., Assefa S. Wheat production and breeding in Sub-Saharan Africa: Challenges and opportunities in the face of climate change // International Journal of Climate Change Strategies and Management, 2019, vol. 11, no. 5, pp. 696-715. https://doi.org/10.1108/IJCCSM-02-2018-0015

55. Туктарова Н. Г. Влияние современных тенденций изменения климата на урожайность озимых зерновых культур // Пермский аграрный вестник. 2019. Т. 25, № 1. С. 80–86.
56. Váry Z., Mullins E., McElwain J.C., Doohan F.M. The severity of wheat diseases increases when plants and pathogens are acclimatized to elevated carbon dioxide // Glob Chang Biol, 2015, vol. 21, no. 7, pp. 2661-2669. https://doi.org/10.1111/gcb.12899
57. Wang B.X., Hof A.R., Ma C.S. Impacts of climate change on crop production, pests and pathogens of wheat and rice // *Frontiers of Agricultural Science and Engineering*, 2022, vol. 9, no. 1, pp. 4-18. https://doi.org/10.15302/J-FASE-2021432
58. Wang Y., Cheng X., Shan Q., Zhang Y., Liu J., Gao C., Qiu J.L. Simultaneous editing of three homoeoalleles in hexaploid bread wheat confers heritable resistance to powdery mildew // Nature Biotechnology, 2014, vol. 32, no. 9, pp. 947-951. https://doi.org/10.1038/nbt.2969
59. Wang W., Pan Q., He F., Akhunova A., Chao S., Trick H., Akhunov E. Transgenerational CRISPR-Cas9 Activity Facilitates Multiplex Gene Editing in Allopolyploid Wheat // CRISPR J., 2018, vol.1, no. 1, pp. 65–74. https://doi.org/10.1089/crispr.2017.0010
60. Yang C., Fraga H., van Ieperen W. et al. Effects of climate change and adaptation options on winter wheat yield under rainfed Mediterranean conditions in southern Portugal // Climatic Change, 2019, vol. 154, no. 1, pp. 159–178. https://doi.org/10.1007/s10584-019-02419-4
61. Zhang Y., Bai Y., Wu G., Zou S., Chen Y., Gao C., Tang D. Simultaneous modification of three homoeologs of TaEDR1 by genome editing enhances powdery mildew resistance in wheat // Plant Journal, 2017, vol. 91, no. 4, pp. 714-724. https://doi.org/10.1111/tpj.13599
62. Zhao C., Liu B., Piao S., Wang X., Lobell D.B., Huang Y., Huang M., Yao Y., Bassu S., Ciais P., Durand J.L., Elliott J., Ewert F., Janssens I.A., Li T., Lin E., Liu Q., Martre P., Müller C., Peng S., Peñuelas J., Ruane A.C., Wallach D., Wang T., Wu D., Liu Z., Zhu Y., Zhu Z., Asseng S. Temperature increase reduces global yields of major crops in four independent estimates // Proceedings of the National Academy of Sciences of the United States of America, 2017, vol. 114, no. 35, pp. 9326–9331. https://doi.org/10.1073/pnas.1701762114
63. Zhu J.H., Dong Y., Xiao J.X., Zhen Y., Tang L. Effects of N application on wheat powdery mildew occurrence, nitrogen accumulation and allocation in intercropping system // Ying yong sheng tai xue bao = The journal of applied ecology, 2017, vol. 28, no. 12, pp. 3985–3993. https://doi.org/10.13287/j.1001-9332.201712.029

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ВКЛАД АВТОРОВ

Диаките С.: сбор и анализ данных, написание рукописи.
Пакина Е.Н.: концепция исследования, редактирование черновика рукописи.
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