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小麦抗低温逆境化控技术研究进展

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摘要: 全球气候变化背景下，极端低温气候灾害事件频发重发已成为影响小麦生产高质高效发展的重要限制因素。为提高小麦的抗低温能力、保障全球粮食安全，前人开展了大量关于外源化控剂缓解小麦低温逆境胁迫的研究。本研究根据 2000 年 1 月 1 日至 2022 年 12 月 31 日公开发表的与小麦抗低温化控技术有关的文献，依据外源化控调控剂的作用机理，将其分为改善光合系统、诱导合成渗透调节物质、提高抗氧化酶活性、激素调节以及影响抗寒基因表达，共 5 大类，并总结了这 5 类作用机理相关的产品开发现状。今后应加强外源化控调控剂缓解低温逆境的机理研究，细化调控剂的施用时期、剂量范围及施用方法，不断优化化控产品生产工艺，以期充分发挥小麦化控抗低温技术在防灾减灾和提质增效中的作用。

关键词: 小麦； 低温胁迫； 化控； 生理机制

Progress of chemical regulation on wheat resistance to low temperature stress

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Abstract: Low temperature stress is a common limiting factor for high quality and high yield of wheat production, many researches have been carried out to alleviate the adverse impact by application of exogenous chemical agents. We searched the published literatures related to low-temperature chemical control in wheat from January 1 of 2000 to December 31 of 2022. According to the mechanism, the exogenous chemical agents regulate the low temperature tolerance of wheat through five paths, i.e. improving photosynthetic efficiency, inducing and synthesizing osmotic adjustment substances, increasing antioxidant enzyme activity, stimulating the synthesis of hormone and up-expressing of cold tolerance genes. We also focused on the progress in production of chemical agents corresponded to each category of the mechanism. In the future, more researches are needed for fully understand the mechanism of exogenous chemical control regulators, efficient application of chemical agents by suitable application period, dosage and method, and further optimize the research and procession technology of chemical agent production, aiming to achieve efficient prevention and mitigation of the adverse impact caused by low temperature on wheat production.

Key words: wheat; low temperature stress; chemical regulation; physiological mechanism

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随着全球人口数量的不断增加，预计到2050年人们对于口粮的需求将增长100%～110%[1]。全世界约33%的人口以小麦为主粮，小麦总产量虽以每年0.9%的速度增长，到2050年其总产量将增加38%，但仍远远低于2050年人们对口粮的需求[2]。据IPCC第六次会议报告，2100年全球地表温度预计将至少升高2.1℃[3]。全球气候变化背景下，西伯利亚高压、阻塞高压和极涡等大气环流异常导致极端低温事件频发[4]，增加了农业生产的不稳定性。小麦的一生易遭受干旱、低温、渍水、高温等逆境胁迫，其中低温逆境已成为影响小麦生长发育和产量品质形成的重要农业气象灾害之一。低温逆境灾害给中国、美国、澳大利亚以及部分欧洲国家的小麦生产造成了极大的损失[5−10]。澳大利亚每年因低温灾害导致小麦减产造成的经济损失达1亿澳元[5−6]。1980—2020年中国小麦主产区发生近20次大规模低温灾害事件[7]。2021年寒潮天气造成江苏省小麦冻害面积达1.36×10^6 hm²，占该省播种总面积的56.68%，严重程度为20年来之最[11]。因此，低温逆境已经成为限制全球小麦生产高产高质高效发展的重要因素。

化学调控技术 (chemical regulation) 是以应用提取的天然植物激素或者人工合成的化学物质等植物生长调节剂为手段，通过改变植物内源激素代谢平衡来调节其生长发育，使其朝着人们预期的方向和程度发生变化的技术。该技术的出现及其在农业生产中的大规模应用，为提高小麦抗低温能力进而防灾减灾与提质增效提供了一条有效途径。小麦抗低温化学调控剂可通过提高叶片超氧化物歧化酶 (SOD)、过氧化物酶 (POD) 和过氧化氢酶 (CAT) 等抗氧化酶的活性和脯氨酸 (Pro)、可溶性糖等渗透调节物质含量来增强细胞膜结构和功能的稳定性[12−13]，同时维持叶片保持较高的净光合速率 (P_n) 和呼吸稳态，进而提升小麦对低温逆境的耐受性[14]。本文根据2000年1月1日至2022年12月31日发表的文献，系统阐述小麦抗低温化学调控剂的种类和作用机理，分析当前抗低温化学调控剂产品研发现状，并对未来小麦抗低温化学调控技术的研究进行展望，以期为小麦生产的防灾减灾和提质增效提供参考。

1 小麦抗低温化学调控剂种类

施用外源化控物质可提高小麦植株的抗低温能力，从而提高小麦生产的防灾减灾能力。根据小麦抗低温化学调控剂所起作用的成分性质，大致可分为无机盐类、有机化合物类、植物激素类、植物生长调节物质、复合型抗寒调节物质等5类 (表1)。

2 小麦抗低温化学调控剂的作用机理

2.1 改善光合性能

光合作用合成的有机物是小麦产量品质形成的物质基础，也是对低温逆境最敏感的生理生化过程之一，其影响方面包括叶绿体结构、叶绿素的合成与分解、Rubisco酶活性、碳同化相关酶基因的表达等[15−22]。朱佳等[19]和范琼花等[20]研究发现低温胁迫前使用硅酸钾盐溶液预处理小麦幼苗可减少叶片叶绿素含量和Chla/b值的降幅，提高Rubisco酶活性从而改善小麦叶片的P_n。苏慧等[21]研究表明，小麦孕穗期低温 (−2℃) 胁迫前喷施15 mmol/L KH_2PO_4溶液，旗叶叶绿素含量与清水对照相比提高了14.8%，能有效降低低温对小麦叶片造成的危害。Venzhik等[22]研究指出，低温 (4℃) 胁迫下施用0.1 mmol/L 脱落酸 (ABA) 可以影响叶绿体基质密度和类囊体的颗粒数，从而保护植物细胞免受冷害和维持光合系统活性。Wang等[23]研究表明，低温胁迫下施用外源水杨酸 (SA) 能使小麦叶片F_v/F_m、ϕPS Ⅱ和P_n分别提升4.9%、5.9%和9.6%，从而提高小麦植株的抗冻能力。因此，化学调控技术主要通过缓解低温逆境对于小麦叶片叶绿体结构的破坏、促进叶绿素的合成等一系列生理生化过程，从而维持叶片较高的光合性能。涉及的外源物包括KH_2PO_4[21]、$CaCl_2$[24]、$(NH_4)_6Mo_7O_{24}$[25]、ABA[26]等 (表2)。

2.2 诱导合成渗透调节物质

小麦植株在低温胁迫下通过合成可溶性糖、可溶性蛋白和Pro等渗透调节物质来提高细胞液浓度从而降低渗透势[33−34]。参与诱导合成渗透调节物质的外源化控剂种类较多[35]，包括表油菜素内酯 (EBR)[12]、SA[36]、Pro[37]、ABA[14,38]、海藻糖[39]、磷钾肥[40]等 (表3)。Li等[41]研究表明，外源NO能诱导叶片果聚糖合成酶基因上调表达，进而影响果聚糖合成酶活性促进果聚糖积累来提高小麦抵抗低温能力。王梦雨等[46]报道施用外源壳寡糖可降低低温胁迫下苗期小麦叶片损伤面积和MDA含量的增幅，返青率可提高5%。刘丽杰等[12]发现，施用0.1 mg/L EBR可使低温胁迫下小麦幼苗中可溶性蛋白、可溶性糖、Pro含量分别显著提升11.2%、142%和457%。Zhang等[47]研究指出施用外源ABA显著提高了低温胁迫下小麦叶片中可溶性蛋白、可溶性糖和Pro含量。上

表 1　抗低温化学调控剂一览表

Table 1　List of anti-low temperature chemical regulators

调控剂 Regulator	缩写 Abbreviation	调控剂 Regulator	缩写 Abbreviation
氯化钙 Calcium chloride	$CaCl_2$	吲哚乙酸 Indole acetic acid	IAA
硅酸钾 Potassium silicate	$K_2Si_2O_5$	细胞分裂素 Cytokinin	CTK
硅酸钠 Sodium silicate	$Na_2SiO_3·9H_2O$	玉米素核苷 Zeatin nucleotide	ZR
磷和钾 Phosphorus and potassium	P and K	赤霉素 Gibberellin	GA
二氧化碳 Carbon dioxide	CO_2	脱落酸 Abscisic acid	ABA
硝普钠 Sodium nitroprusside	SNP	2,4-表油菜素内酯 2,4-Epibrassinolide	EBR
镧离子 Lanthanum ion	La^{3+}	油菜素内酯 Brassinolide	BR
磷酸二氢钾 Potassium phosphate monobasic	KH_2PO_4	茉莉酸甲酯 Methyl jasmonate	MeJA
七钼酸铵 Ammonium heptamolybdate	$(NH_4)_6Mo_7O_{24}$	褪黑素 Melatonin	MT
二甲亚砜 Dimethyl sulfoxide	DMSO	水杨酸 Salicylic acid	SA
海藻糖 Trehalose		美洲星 New meizhouxing	NMX
脯氨酸 Proline	Pro	防冻剂 Antifreeze	
氯化胆碱 Choline chloride	CC	多效唑 Paclobutrazol	PP_{333}
抗坏血酸 Ascorbic acid	ASA	防寒剂 (蔗糖、有机硅) Anti-chilling agent (sucrose, organic Si)	
冠菌素 Coronatine	COR	复配植物生长调节剂 (水杨酸、甜菜碱、硅酸钾) Compound plant growth regulator (salicylic acid, betaine, potassium silicate)	
6-苄氨基嘌呤 6-Benzyladenine	6-BA		

述相关外源物质的施用可有效缓解低温胁迫对于小麦植株渗透调节物质积累的抑制，从而维持细胞结构的稳定性，提高植株的抗低温能力。

2.3　提高抗氧化酶活性

低温胁迫下小麦植株内会产生大量的活性氧 (ROS)，随着低温胁迫程度和胁迫持续时间的增加导致 ROS 清除剂含量和酶活性持续下降，氧化还原平衡被打破，ROS 代谢失调，导致细胞膜脂过氧化最终产物丙二醛 (MDA) 的积累，导致细胞受损甚至死亡[48]。SOD、POD、CAT、ASA 和 GSH 等物质构成了小麦体内的抗氧化防御体系，其活性的高低与小麦抗逆能力密切相关[49−52]。荆恩恩等[53]研究发现，低温 (−5℃) 胁迫前小麦叶面喷施外源 CC 可增强 SOD、POD 和 CAT 活性，降低O_2^-产生速率和 MDA 含量，有效减少膜脂过氧化对细胞的损伤。Yu 等[54]研究表明，外源 ABA 可提高叶片和根茎中抗坏血酸过氧化物酶 (APX)、谷胱甘肽还原酶 (GR)、脱氧抗坏血酸还原酶 (DHAR) 和单脱氧抗坏血酸还原酶 (MDHAR) 活性水平，增强了小麦叶片和根部在−10℃ 和−20℃ 下的抗冻能力。丁美云等[55]研究发现，叶面喷施 0.1 mg/L BR 可使低温 (−25℃) 胁迫下小麦分蘖节 SOD、CAT 和 POD 活性分别提升 41.3%、31.6% 和 14.1%，极大降低了低温冻害对于小麦细胞膜的损伤。因此，化学调控物质主要通过提高抗氧化酶活性，从而降低细胞内自由基含量和产生速率，减轻膜脂过氧化程度，维持细胞膜结构的完整性，进而增强小麦植株的抗低温能力。与诱导抗氧化酶活性有关的外源物质及其施用方式详见表 4。

2.4　激素调节

内源激素是调节小麦生长发育和代谢的一类重要物质。低温胁迫会打破其原有的激素平衡，导致促进生长的激素减少、抑制生长的激素增加从而改变代谢途径。内源激素作为信号分子参与低温胁迫的调控，其中玉米素核苷 (ZR)、GA 和 ABA 在抵御低温过程中起着重要作用[61−64]。Li 等[65]研究表明，在低温 (12℃) 胁迫下施用 5 μmol/L GA 可提高种子呼吸速率和淀粉酶活性促进淀粉分解，提高种子发芽率、胚根和胚芽的重量及长度。齐付国等[66]研究指出，100 μmol/L MeJA 进行叶面喷施幼苗，低温 (4℃) 胁迫下促进了小麦叶片内 ABA 的含量增加和 ABA/GA 值的提高，达到增强小麦抗寒性的作用。Zhang 等[47]研究认为，施用外源 10 μmol/L ABA 增加

表 2 外源调控剂改善作物光合性能的作用机理及最佳施用浓度

Table 2 Mechanism and optimal concentration of exogenous regulators in improving photochemical efficiency

外源调控剂 Exogenous regulator	作用机理 Action mechanism	最佳浓度 Optimal concentration	文献 Reference
硅酸钾 $K_2Si_2O_5$	提高叶片P_n、气孔导度(G_s)、叶绿素含量，降低蒸腾效率，提高水利用效率 Increase leaf P_n, G_s, and chlorophyll content, reduce transpiration efficiency, and enhance water use efficiency	0.1, 1 mmol/L	[19−20]
KH_2PO_4	提高旗叶叶绿素含量和叶片抗氧化能力，增加对穗部的物质供应 Increase flag leaf chlorophyll content and leaf antioxidant capacity, increase material supply to spike	15 mmol/L	[21]
$CaCl_2$	提高Rubisco酶活性、Chla、Chlb与类胡萝卜素(Car.) 含量，促进光合强度 Increase Rubisco enzyme activity, Chla, Chlb & Car. content and promote photosynthetic intensity	40 mmol/L	[24]
$(NH_4)_6Mo_7O_{24}$	提高叶绿素a、b和胡萝卜素含量 Increase Chla, Chlb and Carotene content	0.15 mg/kg	[25]
脱落酸 ABA	增加叶绿素含量，提高叶绿素相对电子传递速率值、最大光化学效率，减少低温对小麦F_v/F_m的不利影响 Increase chlorophyll content, enhance chlorophyll relative electron transfer rate, and maximum photochemical efficiency, and reduce adverse effects of low temperature on wheat F_v/F_m	10^{-5} mol/L	[26]
褪黑素 MT	调节气孔导度和小麦的光合速率，有助于光合碳同化和膜稳定性 Regulate stomatal conductance and photosynthetic rate in wheat and contributes to photosynthetic carbon assimilation and membrane stability	1 mmol/L	[27]
新美洲星 NMX	提高叶片P_n、G_s和胞间CO_2浓度(C_i)、PSⅡ光化学效率、光化学淬灭系数、增加F_v/F_m，改善光合性能 Increase leaf P_n，G_s, and intercellular CO_2 concentrations, PS Ⅱ photochemical efficiency, photochemical quenching coefficient, increased F_v/F_m, and improved photosynthetic performance	300倍稀释液 300 times diluent 10 mol/L	[28]
2,4-表油菜素内酯 EBR	增加叶绿素含量，缓解叶片衰老，延长其功能期 Increase leaf chlorophyll content, mitigate leaf senescence and prolong functional period	0.1 mg/L	[29]
抗坏血酸 ASA	提高叶片叶绿素含量，增加单位面积分蘖数 Increases leaf chlorophyll content and tiller number per unit area	50 mg/L	[30]
二甲亚砜 DMSO	促进小麦幼苗叶绿素的形成，提高根活力 Promote chlorophyll synthesis, increase root vigor of wheat seedlings	2～5 g/kg	[31]
防冻剂 Antifreeze	增加小麦叶绿素含量，促进光合作用，增强根系活力 Increase chlorophyll content, promote photosynthesis efficiency, enhance root vigor	1500 mL/hm^2	[32]

小麦叶片内可溶性糖、Pro、GSH 和 ASA 含量以及相关基因表达，降低 MDA 和 H_2O_2 水平，有效缓解小麦幼苗所受到的低温胁迫。王兴等[62]研究发现，施用 10^{-6} mol/L 6-BA 可促进低温 (−10℃、−25℃) 胁迫小麦叶片和分蘖节中 ABA/GA 的值，降低 GA 含量，提高小麦分蘖节的抗寒能力。化学调节物质可以增加低温逆境胁迫下小麦植株体内多种内源激素含量，促进平衡以及激素间的协同和拮抗作用调节动态平衡，从而提高小麦的抗冻能力 (表 5)。

2.5 抗寒基因的表达

部分抗低温调节物质是小麦在非生物胁迫下的天然积累物，适宜浓度下此类物质可以诱导小麦自身启动抵御低温相关蛋白所关联基因的表达。小麦在低温胁迫下会通过调控相关耐寒基因的表达来应对所处逆境[64,69−70]。Al-Issawi 等[56]研究发现，在低温 (4℃) 驯化下施用外源 8 mmol/L $(NH_4)_6Mo_7O_{24}$ 溶液浸种，显著增加了植株中 *CBF14* 的转录物水平并激活 *COR* 基因。张奥深等[29]研究表明，施用 0.1 mg/L EBR 可以显著提高小麦植株叶片抗逆相关基因 *TaSOD*、*TaPOD*、*TaCAT*、*P5CS* 和 *WCS120* 的相对表达量，从而提高小麦的抗冻性。Zhang 等[47] 研究认为低温胁迫下施用外源 ABA，ASA-GSH 合成相关酶的基因在一定时间内受到 ABA 的调控，使小麦叶片中 ASA 和 GSH 显著提高以及相关基因 *CBFII-5.2*、*WCS120*、*COR39* 和 *Wrab17* 转录水平提高。赵欣等[71]研究指出，SA 处理提高了小麦叶片和分蘖节中 EMP 途径关键酶 HxK、PFK、PK 的活性及其相应基因 *TaHxK*、*TaPFK*、*TaPK* 的表达量，促进果糖与丙酮酸的积累与分解，提高小麦植株的抗低温能力。

表 3　诱导渗透调节类物质合成的外源物质施用方法

Table 3　Application method of exogenous substances inducing synthesis of osmoregulation substances

外源物 Exogenous substance	使用方法 Application method	施用浓度 Application concentration	试验温度 (℃) Temperature	文献 Reference
表油菜素内酯 EBR	叶面喷施 Foliar spraying	0.1 mg/L	4	[12]
硅酸钾 $K_2Si_2O_5$	水培 Hydroponics	1.0 mmol/L	−5	[20]
二甲亚砜 DMSO	浸种 Seeding soaking	2～5 g/kg	4	[31]
水杨酸 SA	水培 Hydroponics	100 μmol/ L	4	[36]
脯氨酸 Pro	叶面喷施 Foliar spraying	20 mmol/L	−5	[37]
脱落酸 ABA	根浸、叶面喷施 Root soaking, foliar spraying	10^{-7} mol/L	2～4	[38]
海藻糖 Trehalose	浸种 Seeding soaking	10 mmol/ L	4	[39]
磷钾 P and K	水培 Hydroponics	P_2O_5 52 mg/L K_2O 104 mg/L	5	[40]
硝普钠 SNP	水培 Hydroponics	0.125 mmol/L	4	[41]
$Na_2SiO_3·9H_2O$	浸种 Seeding soaking	1.0 mmol/L	0, 4	[42−43]
茉莉酸甲酯 MeJA	叶面喷施 Foliar spraying	1.0 mmol/ L	5 , 0 , −10 , −25	[44]
冠菌素 COR	浇灌培养 Irrigating	1 μmol/L	4	[45]

表 4　外源调节抗氧化酶活性类物质使用方法

Table 4　Application method of exogenous substances regulating antioxidant enzyme activities

外源物 Exogenous substance	使用方法 Application method	施用浓度 Application concentration	试验温度 (℃) Temperature	文献 Reference
表油菜素内酯 EBR	叶面喷施 Foliar spraying	0.1 mg/L	4	[12]
硝普钠 SNP	浸种 Seeding soaking	50 μmol/L	4	[13]
抗坏血酸 ASA	浸种 Seeding soaking	50 mg/L	—	[30]
$Na_2SiO_3·9H_2O$	浇灌 Irrigating	1.0 mmol/L	0, 4	[43]
氯化胆碱 CC	叶面喷施 Foliar spraying	500 mg/L	−5	[53]
$(NH_4)_6Mo_7O_{24}$	浸种 Seeding soaking	8 mmol/L	4	[56]
多效唑 PP_{333}	浸种 Seeding soaking	0.01 mg/L	3	[57]
水杨酸 SA	叶面喷施 Foliar spraying	0.1 mmol/L	4	[58]
镧离子 La^{3+}	水培 Hydroponics	20 mg/kg	0, 5, 10	[59]
茉莉酸甲酯 MeJA	水培 Hydroponics	1 μmol/L	4	[60]
CO_2	激光辐射 Laser radiating	10600 nm (Wavelength)	4	[13]

注：“—”表示文献中未注明。

Note: “—” indicates that it is not listed in the reference.

3　小麦抗低温化学调控产品

目前，小麦抗低温化学调控产品的开发应用逐渐受到人们的重视。截至 2022 年 12 月 31 日，涉及作物抗低温化学调控剂的国家发明专利共 93 件，其中小麦抗低温化学调控剂发明专利为 27 件，占 29.03%，且专利公开年份均在 2010 年之后 (图 1)。这可能与近年来全球气候变暖导致极端低温气候事件出现的频率、强度和持续时间不断增加，已成为限制小麦稳产丰产与优质的重要因素有关，同时也表明小麦抗低温化学调控剂具有巨大的潜在市场价值。本研究归纳整理了近年来有关小麦抗低温化学调控产品的发明专利 (表 6)。

表 5 外源激素调节机理及施用浓度

Table 5 Mechanism and application concentrations of exogenous hormones

外源激素 Exogenous hormone	作用机理 Action mechanism	施用浓度 Application concentration	文献 Reference
脱落酸 ABA	增加小麦叶片内可溶性糖、Pro、谷胱甘肽(GSH)和ASA含量以及相关基因表达 Increase leaf soluble sugars, Pro, GSH and ASA content, and upregulate related gene expression	10 μmol/L	[47]
吲哚乙酸 IAA	增加根系IAA含量 Increase root IAA content	—	[51]
玉米素核苷 ZR	缓解低温胁迫对小麦植株的伤害 Mitigate low-temperature injury to wheat plants	—	[61]
6-苄氨基嘌呤 6-BA	增加叶片和分蘖节中ABA/GA值，提高翌年返青率 Increase ABA/GA ratio in leaves and tiller nodes, improve regreening rate next year	10 μmol/L	[63]
赤霉素 GA	增加种子呼吸速率和淀粉酶活性，促进淀粉分解，提高了种子发芽率、萌发指数以及胚根和胚芽发育 Increase seed breathing rate and amylase activity, promote starch decomposition, seed germination, germination index, and embryonic root and germ development	5 μmol/L	[65]
茉莉酸甲酯 MeJA	提高小麦叶片内ABA含量以及ABA/GA值，维护激素平衡 Increase leaf ABA content and ABA/GA ratio, maintain hormone balance	100 μmol/L	[66]
水杨酸 SA	促进低温下种子萌发，提高叶片中可溶性糖积累 Promote seed germination at low temperatures, and increase osmoregulatory accumulation in leaves	0.005～0.100 mmol/L	[67]
细胞分裂素 CTK	增加小麦幼苗抗寒能力 Increase cold tolerance of wheat seedlings	—	[68]

注：“—”表示文献中未注明。

Note: “—” indicates that it is not listed in the reference.

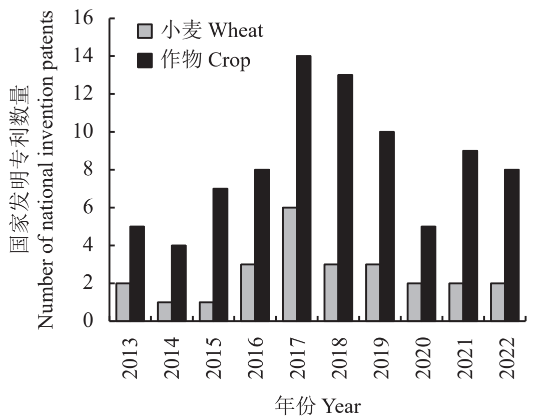

图 1 2013—2022 年抗低温化学调控剂国家发明专利数量

Fig. 1 Number of national invention patents of chemical regulators for low temperature resistance during 2013−2022

4 总结与展望

根据作用机理，外源化学调控剂可分为改善光合系统、诱导合成渗透调节物质、诱导抗氧化酶活性、激素调节以及影响抗寒基因表达等共 5 大类。目前小麦生产对抗低温化学调控剂的需求不断增加，然而现有抗低温化学调控剂在生产中的推广应用效果并不理想，主要是因为生产成本较高，比如 ABA、MeJA 等由于价格昂贵，一般农户无法接受，难以大面积应用于农业生产。因此未来应重点开展以下几个方面的研究：

1) 加强外源化学调控剂缓解低温逆境的机理研究。因小麦品种抗性、生长环境和栽培措施的不同和差异化，化控剂作用机理有待进一步深化，如 KH_2PO_4 作为一种绿色无毒、高效的水溶性速效磷钾复合肥，因具有提高植株的抗低温能力而广泛应用于小麦生产中，但其提升小麦抗低温能力的生理与分子机制至今仍未明确。

2) 在明确化学调控剂作用机理的基础上，进一步研究明确小麦抗低温化学调控剂的施用时期、剂量范围及施用方法。在田间试验阶段要针对产品药效、毒理学、环境毒理和环境行为及残留代谢等进行完整的评价，同时可结合农事操作进一步调查其农学效应，比如产品的使用与小麦拔节肥或者生育中后期的“一喷三防”有机结合，尤其是与现代无人机的飞防结合，研发简便易操作的应用技术，将具有广阔的应用前景。

3) 加强产品的生产工艺研究与优化。降低小麦抗低温化学调控剂的生产成本，寻找价廉且抗低温逆境效果好的原材料来制备抗低温化学调控剂，同

表 6　小麦抗低温化学调控剂专利名录及产品有效成分

Table 6　List of patent products and the effective components for low temperature resistance of wheat

专利名称 Patent name	主要有效成分 Main effective component	公开年份 Public year	文献 Reference
一种小麦抗低温保护剂及使用方法 A wheat anti-low temperature protective agent and the use method	甜菜碱、蚯蚓活性酶植物多肽液、尿素、磷酸二氢钾、壳聚糖 Betaine, plant peptide solution with earthworm active enzymes, urea, potassium dihydrogen phosphate, chitosan	2022	[72]
一种提高小麦抗逆潜力和灾后恢复力制剂及应用 A product to improve the resistance potential and post-disaster recovery of wheat and the use method	复合氨基酸、氯化钙、5-氨基乙酰丙酸、芸苔素内脂 Aminofusin, calcium chloride, 5-aminolevulinic acid, brassinolide	2022	[73]
一种提高小麦春季抗寒性的复配剂、施用方法及其应用 A formula agent for improving wheat tolerance to spring cold and the application method	6-BA、壳寡糖、2, 4-表油菜素内酯、冠菌素 6-Benzylaminopurine, chitosan oligosaccharide, 2,4-epibrassinolide, coronatine	2021	[74]
一种小麦抗低温诱导剂产品及使用方法 A wheat anti-low temperature inducer and the use method	蚯蚓活性酶植物多肽液、壳聚糖、尿素、磷酸二氢钾、茉莉酸甲酯 Plant peptide solution with earthworm active enzymes, chitosan, urea, potassium dihydrogen phosphate, methyl jasmonate	2021	[75]
一种用于小麦倒春寒的防寒剂 An anti-chilling agent of late spring coldness in wheat	蔗糖、有机硅 Sucrose, silicone	2020	[76]
一种小麦抗寒诱导剂及其施用方法 A wheat cold resistance inducer and the application method	蛋氨酸铜、松脂醇二葡萄糖苷、水杨酸、壳寡糖、氯化钙 Copper methionine, pinoresinol diglucoside, salicylic acid, chitosan oligosaccharide, calcium chloride	2020	[77]
一种呋喃并吡喃衍生物及其制备方法和在小麦田间防冻管理中的应用 A furopyran derivative and its procession protocol, and application method preventing wheat from frost injury	一种呋喃并吡喃衍生物 A furopyran derivative	2019	[78]
一种抵御小麦倒春寒的混合制剂及其制备和喷施方法 Procession and foliar application method of a formula agent for wheat resistance to late spring coldness	尿素、磷酸二氢钾、硫酸锌、胺鲜酯、康多酚 Urea, potassium dihydrogen phosphate, zinc sulfate, diethyl aminoethyl hexanoate, kang polyphenol	2019	[79]
一种适用于小麦的防冻剂及制备方法和应用 Procession and application of an antifreeze agent for wheat	硫酸铵、磷酸二氢钾、硫酸钾、乙二胺四乙酸锌、壳寡糖、脯氨酸、芸苔素、甘油 Ammonium sulfate, potassium dihydrogen phosphate, potassium sulphate, ethylenediaminetetraacetic acid zinc, chitosan oligosaccharide, proline, brassinolide, glycerol	2019	[80]
一种性激素在小麦孕穗期抗寒减灾方面的应用 Application of a hormone for alleviating low temperature injury of wheat at booting stage	孕酮 Progesterone	2018	[81]
一种小麦耐旱抗逆复合调节剂及其应用 A compound regulator for drought and stress tolerance in wheat and its application	甜菜碱、果聚糖、壳聚糖、油菜素内酯、硝普钠、黄腐酸、柠檬酸钛 Betaine, fructosan, chitosan, brassinolide, sodium nitroprusside, fulvic acid, citric acid titanium	2018	[82]
一种小麦抗病防冻农药组合物 An anti-disease and anti-freeze pesticide composition for wheat	已唑醇、氯化胆碱、香菇多糖 Hexaconazole, choline chloride, lentinan	2018	[83]
一种提高小麦抗冻能力的专用液体肥料 A specific liquid fertilizer to improve the frost resistance of wheat	醋酸铜、柠檬酸螯合锰、山梨酸钾、乙基麦芽酚、L-谷氨酸 Cupric acetate monohydrate, citric acid chelated manganese, potassium sorbate, ethyl maltol, L-glutamic acid	2017	[84]
防御小麦春季冻害的复合调节剂及方法 Compound regulators for preventing spring frost damage in wheat and the use method	水杨酸 Salicylic acid	2017	[85]

续表 6 Table 6 continued

专利名称 Patent name	主要有效成分 Main effective component	公开年份 Public year	文献 Reference
一种小麦抗寒诱导剂及其施用方法 A wheat cold resistance inducer and its application method	氨基寡糖素、聚乙二醇、脂肪酶、乙基磺酸乙酯、海藻酸、青鲜素 Amino-oligosaccharides, polyethylene glycol, lipase, diethyl sulfite, alginic acid, maleic hydrazide	2017	[86]
小麦抗低温调节剂及其使用方法 A regulator for low temperature resistance of wheat and the use method	褪黑素、腐殖酸钾、α-萘乙酸、茉莉酸、油菜素内酯、细胞分裂素、抗冻剂、抗菌肽 Melatonin, potassium humate, α-Naphthaleneacetic acid, jasmonic acid, brassinolide, cytokinin, antifreeze, antimicrobial peptide	2017	[87]
一种提高小麦抗低温冷害的抗冷剂及其应用方法 A cold-resistant agent for improving resistance to low-temperature damage of wheat and the application method	磷酸氢二钠、磷酸二氢钾、甜菜碱、硝基腐殖酸铵、硝普钠、蔗糖、尿素 Dibasic sodium phosphate, potassium dihydrogen phosphate, betaine, ammonium nitro-humate, sodium nitroprusside, sucrose, urea	2017	[88]
小麦抗低温调节剂及其使用方法 A regulator for wheat low-temperature resistance and the use method	甜菜碱、壳寡糖、水杨酸、硅酸钾、蛋白多肽 Betaine, chitosan oligosaccharide, salicylic acid, potassium silicate, protein polypeptides	2017	[89]
一种小麦抗寒诱导剂及其施用方法 A wheat cold resistance inducer and the application method	双氧水、水杨酸 Hydrogen peroxide, salicylic acid	2016	[90]
提高小麦抗低温能力的调理剂 A conditioning agent to improve wheat resistance to low temperatures	6-BA、萘乙酸盐、甲哌鎓、乙烯利、磷酸二氢钾 6-Benzylaminopurine, naphthalene acetate salt, mepiquat chloride, ethrel, potassium dihydrogen phosphate	2016	[91]
一种小麦高光效抗逆境增产调节剂及其制备方法和应用 An regulator for improving photosynthetic efficiency, stress resistance and yield of wheat, and its manufacture and application	5-氨基乙酰丙酸、萘乙酸盐 5-aminolevulinic acid, naphthalene acetate salt	2016	[92]
一种提高冬小麦抗冻能力的方法 A method to improve winter wheat resistant to frost	四氢嘧啶及其衍生物 Ectoine and its derivatives	2015	[93]
一种小麦抗寒调节剂 A regulator for cold resistance of wheat	浒苔多糖、水杨酸、油菜素内酯、甜菜碱、亚精胺 *Enteromorpha prolifera* polysaccharide, salicylic acid, brassinolide, betaine, spermidine	2014	[94]
一种预防小麦低温冻害的专用烟雾剂及其制备方法 A special fogging agent for preventing low-temperature damage of wheat and its manufacture method	柴油、丙二醇、尿素、磷酸二氢钾、氯化钾 Diesel oil, propylene glycol, urea, potassium dihydrogen phosphate, potassium chloride	2013	[95]
小麦抗低温调节剂及其制备方法 A wheat anti-low temperature regulator and its producing method	氨基多糖、氯化胆碱、水杨酸或水杨酸钠、硅酸钾 Aminopolysaccharide, choline chloride, salicylic acid or sodium salicylate, potassium silicate	2013	[96]

时对现有生产方法进行工艺优化，从而降低成本，实现规模化生产，将极大地提高我国小麦生产的防灾减灾能力。

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