▪ 作物水肥高效利用 ▪

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秸秆还田对土壤理化性质及水肥状况影响的研究进展

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摘 要：农作物秸秆是农作物的重要光合产物和最主要的副产品，资源十分丰富。其富含氮、磷、钾等元素，是农业生态系统中一种十分宝贵的生物质资源，利用潜力巨大。秸秆还田是最主要的秸秆资源化利用方式，具有改良土壤、保水控盐和培肥增产等显著效果。本文系统整理和总结了 2012 年以来秸秆还田对土壤理化性质、水盐运移、土壤肥力及作物产量、负面影响及防治措施的研究进展，探究其影响规律和作用机理，探寻不同秸秆还田处理方式的适用性。整理归纳了秸秆还田配合不同耕作方式、添加物及预处理和粉碎程度等改善土壤理化性质的研究概况，总结了秸秆改善土壤理化性质作用机理；对比分析了秸秆还田量、埋深、长度和还田方式等对秸秆还田调控水盐运移的影响，探究了秸秆保水控盐的作用机理；总结概述了秸秆还田提升土壤肥力，促进作物增产的研究成果，提出了配施氮肥，加快秸秆腐解和注意土壤初始水肥条件等合理建议；阐述介绍了当前秸秆还田面临的主要问题及其防治措施；最后，在前人的研究基础上提出了秸秆还田实际应用的部分注意事项，并对未来潜在研究方向进行了展望。以期为秸秆资源化利用、盐渍土改良、农业高效生产等方面的研究、应用与决策提供有价值的参考依据。

关 键 词：秸秆还田；土壤团聚体；水盐运移；土壤肥力；土壤改良
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0 引 言

我国是农业大国，农作物种植是我国的根基产业。作为农作物种植产生的最主要副产品，秸秆年产量十分巨大，年产量超 8 亿 t，居世界首位[1]。然而，受限于收集方式、利用技术和运输成本等因素，我国早年秸秆资源化利用程度较低，处理方式以焚烧、废弃为主，不仅造成资源浪费，而且导致环境污染。近年来，我国把农业资源综合利用纳入生态文明建设总体布局，不断完善法规政策，加大财政支持，健全标准规范，强化科技支撑，推动包括秸秆在内的农业废弃物资源的高效利用，秸秆资源化利用率大幅度提高。《第二次全国污染源普查公报》显示，2017 年全国秸秆产生量为 8.05 亿 t，秸秆可收集资源量为 6.74 亿 t，秸秆利用量为 5.85 亿 t[2]，综合利用率 72.7%。有关分析报告表明，2019 年，我国秸秆的综合利用率达到 86%，2020 年为 90%[3]。秸秆利用方式及比例图 1 所示，其中秸秆直接还田为最主要的利用方式，占比 39%左右[3]。

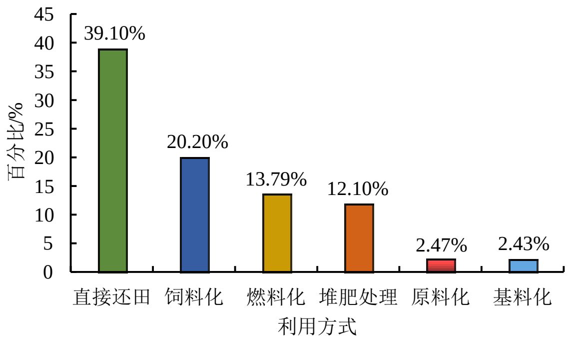

图 1 我国 2020 年秸秆利用方式及比例

Fig.1 Utilization mode and proportion of straw in China in 2020

近年来，众多学者针对秸秆还田改善土壤理化性质、调控水盐运移和提升土壤肥力等方面，进行了大量深入的研究，成果丰硕。相关研究已证明，秸秆还田可降低土壤体积质量，提高土壤孔隙度，促进大团

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聚体形成，改良土壤结构，提升土壤稳定性；增加土壤含水率，抑制土壤盐分表聚，有效改良盐渍土；增加土壤碳、氮、钾、磷等营养物质，提升土壤肥力，促进作物增产。对于稳定农业生态平衡、发展循环经济、构建资源节约型社会、减轻环境压力都具有十分重要的意义。

本文全面、系统地整理和总结了 2012 年以来不同秸秆还田措施对土壤理化性质、水盐运移、土壤肥力和作物生长及产量影响的研究，探究其影响规律和作用机理，探寻不同秸秆还田处理方式的适用性，为秸秆资源化利用、盐渍土改良、农业高效生产和生态环境可持续发展等方面的研究、应用与决策提供有价值的参考依据。

1 秸秆还田改善土壤理化性状

秸秆还田是改善土壤理化性质的重要农艺措施之一。秸秆还田可促进土壤中<0.25 mm 粒径颗粒向>0.25 mm 粒径水稳性团聚体团聚，导致大粒径（>2 mm、0.25~2 mm）水稳性大团聚体比例显著增加，小粒径（0.25~0.053 mm、<0.053 mm）水稳性微团聚体的比例显著降低[4-7]，团聚体稳定性明显增强[8-9]；可显著提升土壤平均重量直径（MWD）、几何平均直径值（GMD）、水稳系数（K）和有机碳量（SOC），降低土壤体积质量，提高土壤孔隙度[10-15]。从而改良土壤结构，提升土壤稳定性。

1.1 秸秆还田配合适当耕作方式提升改良效果

秸秆还田配合深耕、旋耕等耕作方式，显著改善不同深度土层的理化性质。邹文秀等[16]研究发现，在东北平原地区（黑土，质地：壤黏土）采用玉米秸秆还田配合深耕翻和超深耕翻促进底层土壤重组，增加耕层厚度，扩大土壤持水率，增强土壤水分调节能力，大幅改善 20~35 cm 和 35~50 cm 土层的物理性质。董建新等[17]研究表明，在黄淮地区（褐土，质地：壤质黏土）采用玉米秸秆颗粒化还田配合深翻和旋耕，可降低 0~20 cm 和 20~40 cm 土层的土壤体积质量，提升田间持水率、土壤孔隙度和团聚体稳定性。薛斌等[18]研究发现，江汉平原地区（水稻土，质地：壤土、粉质壤土）采用水稻秸秆还田配合传统耕作的土壤体积质量降低较明显，免耕则增加土壤体积质量。庞党伟等[19]对比研究发现，泰莱平原地区（潮褐土，质地：黏壤土）玉米秸秆不还田时，采用连续旋耕的耕作方式会导致 0~30 cm 土层的有机质量下降，土壤体积质量增大，孔隙度降低；但秸秆还田后，相应的结果正好相反；连续 2 年旋耕加 1 年深耕的效果更佳。张玉铭等[20]比较了华北平原地区（潮褐土，质地：黏壤土）玉米秸秆旋耕还田和深翻耕还田对土壤团聚体的影响，结果表明秸秆深翻耕还田促进 0~40 cm 土层土壤有效融合，消除了耕层土壤养分表聚现象，明显提升了 20~40 cm 土壤有机碳氮量以及大团聚体对土壤有机碳氮的贡献率。实际应用时，可结合种植作物生长特点选择适宜耕作方式，提升秸秆还田改良效果。

1.2 秸秆联合生物炭、化肥、氨化处理增强改善作用

秸秆与生物炭、化肥、氨化处理联合使用，可进一步提升土壤理化性质改良的效果。秸秆和生物炭联合施用效果优于秸秆或生物炭单独使用，显著促进土壤大团聚体形成，提高团聚体有机碳量[21]，提升土壤 pH 值和土壤饱和导水率（SHC）[22]。秸秆还田配施化肥处理可增加>0.25 mm 团聚体量，降低 0.053~0.25 mm 和<0.053 mm 团聚体量；提高 0~20 cm 和 20~40 cm 土层团聚体稳定性，并显著提高土壤有机碳量，团聚体稳定性显著增强，效果比单施化肥更显著[23-25]。紫云英配合秸秆全量还田施用也有相似的效果[26]。将秸秆粉碎至粉末状，并氨化处理后还田，可有效促进土壤已有孔隙向更大孔隙发展，提高土壤总孔隙度[27]，耕层土壤体积质量、大团聚体量、平均重量直径（MWD）、几何平均直径（GMD）等指标明显优于传统秸秆还田[28]。未来可进一步研究秸秆还田联合不同肥料、秸秆预处理或添加剂对土壤理化性质的影响，制定更优配合比，不断优化秸秆还田效果。

1.3 秸秆粉碎程度对土壤结构的影响

秸秆粉碎程度不足时，秸秆以段状为主，若与土壤混合不均匀，易使耕层土壤内部形成空洞，导致根系无法与土壤颗粒有效接触，影响播种质量和根系生长；同时空洞还会导致土壤水分和温度加快流失，影响后茬作物秧苗生长[29]。随秸秆还田量和还田频率的增加，上述危害会进一步加剧。Zhang 等[30]研究发现与 10 cm 和 20 cm 小麦秸秆相比，5 cm 段状小麦秸秆还田对土壤孔隙度、体积质量等物理性质的改善效果显著上升。张宏媛等[31]利用 CT 扫描技术对比分析了 5 cm 段状玉米秸秆和 2 mm 粉末玉米秸秆的孔隙形态特征，发现 2 mm 粉末秸秆孔隙数量多、分布均匀，呈现明显的复杂多孔结构。因此，实际生产时应提高秸秆粉碎程度，减小秸秆长度，建议以<5 cm 段状或粉末状秸秆还田为宜，并应确保秸秆与土壤充分均匀混合。

1.4 秸秆还田改善土壤理化性质的作用机理

秸秆还田改善土壤理化性质的原因主要是：①秸秆本身为有机物料，腐解后向土壤输送大量有机碳氮物质，并产生多糖、蛋白质、木质素等有机质；土壤有机质是团聚体形成的重要胶结物质，可促进土壤中矿物和黏粒胶结形成大团聚体[22, 32-35]；②秸秆还田增加土壤有机质量，提升土壤通气性能，改善土壤微生

态环境，提高土壤微生物活性，促使作物根系分泌或溢泌出更多的有机化合物，进一步促进大粒径团聚体形成[5, 12, 36]；③秸秆还田为蚯蚓、蚂蚁、蟋蟀等动物提供了丰富的食物来源和适宜的生活环境，土壤中动物的数量增加。动物通过摄食、穿行、排泄等活动，疏松土壤，提高土壤孔隙率，驱动土壤碳氮循环，加快秸秆腐化[37]。这些因素共同作用，有效促进了土壤大团聚体的形成，显著提升土壤稳定性。

2 秸秆还田调控土壤水盐运移

全世界约 1/4 耕地受到盐渍化影响[38]。盐渍化土壤含盐高，结构差，孔隙少，渗透差，养分低，微生物群落结构和活性差[39-41]，严重阻碍了作物正常生长，极大程度限制了农业高效生产，对粮食安全生产、耕地红线造成严峻威胁，亟须改良。秸秆还田可显著影响土壤水盐运移，增加土壤含水率，减少土壤水分蒸发，抑制土壤盐分表聚，具有保水控盐的作用，有效改良盐渍土[42-44]。

2.1 秸秆还田量对土壤水盐运移的影响

秸秆对水盐运移的影响与还田量有关，总体上，秸秆保水控盐效果与还田量呈正相关关系，表层积盐量、土壤蒸发强度和累积蒸发量与秸秆还田量呈反相关关系[45-48]。范雷雷等[45]在河套灌区研究发现，不同玉米秸秆覆盖时 0~80 cm 土壤层含盐量均有所减少，其中覆盖量 1.2 kg/m^2 和 0.9 kg/m^2 处理抑制效果最优，增幅为初始含盐量的 14.10%和 24.74%。梁建财等[46]发现，在河套灌区玉米秸秆覆盖可提高 0~100 cm 土壤含水率，降低土壤含盐量；相对于未覆盖秸秆处理，秸秆覆盖量 0.6 kg/m^2 及以上均可使土壤表层达到脱盐效果，保水脱盐效果随还田量增加而显著提升。邓亚鹏等[47]研究了黄河三角洲地区小麦秸秆覆盖秋浇后盐渍土壤水盐运移的特征，结果表明，秸秆覆盖抑制消融水蒸发，0.9 kg/m^2 处理的土壤含水率最高；减弱土壤积盐，1.2 kg/m^2 和 0.6 kg/m^2 分别在 0~10 cm 和 0~40 cm 土层中的脱盐效果最好。李小牛等[48]研究结果表明：秸秆层以上的田间持水率与玉米秸秆还田量成正比，添加玉米秸秆后的 0~20 cm 土壤层含水率均高于土壤层田间持水率。当然，秸秆还田量并非越多越好，当秸秆还田量过多时，秸秆腐解问题凸显，加剧土壤空洞，不利于作物生长。

2.2 秸秆埋深和长度对土壤水盐运移的影响

秸秆埋深和长度对土壤水盐运移也有一定影响。除常规表层覆盖还田外，近年来将秸秆埋入地下一定深度形成隔离层的方法也开始研究和应用。秸秆埋深方面，李芙荣等[49]研究了苏北平原地区不同玉米秸秆埋深（0/40/70/40+100 cm 双层）对土壤水盐分布及其动态变化的影响。结果表明，不同玉米秸秆埋深对土壤含水率变化影响较小，除了 70 cm 埋深，其他埋深处理对盐分表聚的抑制效果较好，其中（40+100）cm 双层埋深处理的保水控盐效果最佳。张金珠等[50]研究发现，在北疆石河子，小麦秸秆埋深 30 cm 可阻碍 35 cm 以下土壤毛管水上升，从而影响土壤水盐运移。王学成等[51]设计了不同棉花秸秆埋深（10/15/30/45 cm）对土壤水盐分布和棉花根系构型的影响，结果表明，在南疆阿拉尔，棉花秸秆埋深对二者影响显著，土壤虚实程度有所差异，土壤水盐分布发生变化，其中，埋深 30 cm 可促进棉花根系生长。秸秆长度方面，张宏媛等[31]对比分析了 5 cm 段状玉米秸秆、玉米秸秆颗粒和玉米秸秆粉末对秸秆层孔隙度和灌溉水入渗等的影响，试验表明，5 cm 段状玉米秸秆隔层孔隙度随深度变化较明显，其淋洗时水分优先流现象最显著，持续时间较长。张金珠等[52]研究不同小麦秸秆长度（1/10 cm）的秸秆隔层对盐渍土入渗过程土壤水盐分布的影响，结果表明，小麦秸秆长度影响盐分滞留深度，秸秆 10 cm 比 1 cm 处理的全盐量最大值深度有所下移。在实际应用时，应结合土壤水盐分布情况和作物生长特点，针对性调整秸秆埋深和秸秆长度，调控土壤水盐运移，确保作物处于适宜的水盐环境。

2.3 秸秆还田方式对保水控盐效果的影响

不同的秸秆还田方式对保水控盐效果的影响有所差异。不同学者对比分析了秸秆表层覆盖、秸秆掩埋、秸秆覆盖+掩埋等还田方式的保水控盐效果，所得结论基本一致，即秸秆覆盖+掩埋方式更能抑制水分蒸发和盐分表聚，效果优于单一处理[53-56]。秸秆表层覆盖可抑制蒸发，掩埋作为隔层可储蓄水分，促使 0~30 cm 土层保持“高水低盐”状态，适宜作物生长。此外，秸秆还田与覆膜、覆砂等农技措施配合使用，可有效提升保水控盐效果。部分学者对比研究了秸秆覆盖、秸秆掩埋、上秸下秸、上膜下秸、地膜覆盖等处理对土壤保水控盐效果的影响，结果表明，不同措施的土壤保水控盐效果与作用时期不同，且差异较大；上膜下秸的效果最佳，时效最长，能控制整个作物生育期[57-60]。赵文举等[61]设置覆砂、覆膜、覆麦秸秆单独或二者组合使用，研究发现不同处理均可显著减少土壤水分蒸发，但保水效果有所差异，总体上，覆砂的保水效果优于覆秸秆，二者搭配使用效果更佳。因此，可采用多层秸秆复合还田方式，进一步提升秸秆保水控盐的效果。

2.4 秸秆还田调控土壤水盐运移的作用机理

关于秸秆还田调控土壤水盐运移的作用机理，学者们研究结论大致相同，主要如下：①淋洗入渗阶段，秸秆隔层与上覆土层存在孔隙差异，土-秸界面处水

势差逆向，延缓湿润锋推进速度，秸秆隔层表现出阻水减渗的效果，即“毛细阻滞”[62-63]，导致土壤含水率上升；随着秸秆隔层含水率的不断增加，其导水率也不断上升，当秸秆隔层含水率达到饱和时，秸秆隔层导水率大于周边土壤导水率，产生二次阻碍[64]，即“水力阻滞”，导致上层水分入渗进一步减缓，同时减少下层水分上升。土壤水分因“毛细阻滞”和“水力阻滞”影响而延缓入渗，土壤水分在耕层土壤的蓄积时间延长，土壤含水率升高，促进了土壤中可溶性盐离子的交换和溶解，待重力水完全下渗后，带走更多的盐分离子，提升淋洗脱盐效果[30,64]；②在蒸发阶段，由于秸秆隔层阻断了毛管水上升路径，地下水沿土壤毛管上升至隔层后只能以水汽扩散的形式穿越秸秆层及以上的土壤进入大气，潜水蒸发能力大幅减弱，从而有效抑制了地下水或深层土壤中的盐分向上运移，大幅降低土壤返盐量[65-66]。

3 秸秆还田提升土壤肥力，促进作物增产

大量研究表明[67-78]，秸秆腐解能提高土壤中碳、氮、钾、磷等营养物质，增加土壤微生物的数量和活性，促进有机物分解和养分释放，提升土壤肥力，同时创造适宜环境，有利于作物生长和产量及品质的提高。

3.1 秸秆还田培肥增产效果明显

随着秸秆还田腐解，秸秆中营养物质逐步分解释放，从而显著提升土壤肥力，有效提高作物水分利用效率、氮肥农学利用效率、氮肥偏生产力、氮肥吸收利用率等生长指数[79-82]，促进作物生长，提高作物产量及品质。陈金等[83]研究发现玉米秸秆还田大幅度提高冬小麦全生育期干物质积累总量，降低开花前干物质积累量及其占全生育期比例。刘艳慧等[84]探究得到长期棉花秸秆还田可培肥地力，提高棉花总铃数、单铃重和产量。张学林等[85]研究结果显示，与秸秆不还田处理相比，小麦秸秆还田后可显著提高玉米穗行数、行粒数、穗粒数、千粒质量、籽粒蛋白质、淀粉量和产量，脂肪量降低。同时，秸秆还田还具有调控土壤温度、改善土壤微生物和缓解盐分胁迫等作用，促进作物增产。研究表明，秸秆覆盖还田对土壤温湿度具有双向阻碍作用，保温保墒，有利于玉米生长和产量提升[86]。浅埋秸秆隔层可有效缓解植株受到盐分胁迫，有利于番茄植株的光合作用和相关生理参数，提高番茄产量及品质[87-88]。此外，对秸秆进行氨化、堆肥等处理后还田可提升改善效果。氨化秸秆还田具有良好的蓄水保墒能力，增加夏玉米、冬小麦等作物的叶面积指数，提高作物水分利用率和产量，促进地上部干物质积累，相关指标提升明显优于传统秸秆还田[89-90]。低温堆腐秸秆还田可以改善土壤微生物群落结构，提升土壤肥力，实现玉米增产[91]。

3.2 秸秆配合氮肥施用培肥增产效果更佳

秸秆还田可能会造成土壤 pH 值升高，改变硝化和反硝化过程，提高土壤氨挥发，导致土壤氮素损失[92]；此外，由于秸秆碳氮比较高，秸秆腐化过程中微生物大量增殖消耗土壤速效氮，导致土壤氮素不足，影响作物生长，造成减产。因此，秸秆还田应配合化肥施用，尤其是氮肥，降低碳氮比，加速秸秆降解，降低化感抑制效应[93]，避免还田腐解前期与微生物“争氮”产生的不利影响，并提高作物氮肥农学利用率[94]。研究表明，秸秆还田配氮肥可激发氮的矿化作用，显著增强土壤供氮能力；同时，加速秸秆腐败，增加土壤有机质，提升土壤营养元素吸附力，弥补微生物在秸秆降解过程中对养分的固持[95]，显著提高土壤中有机碳和总氮量[96]，并可将总氮储存在上部根区，在有限的条件下减轻氮和灌溉水的负面影响[97]，从而提升培肥增产效果。此外，秸秆还田配合氮肥施用，可有效降低氮肥施用量，与单施氮肥相比，降幅可达15%~30%[98-100]，不仅提升作物产量，还能降低化肥成本，同时减轻农业面源污染。

3.3 土壤水肥条件对秸秆还田增产效果有差异

土壤水肥条件不同，秸秆还田效果可能有所差异，前期研究结论尚未一致，有待进一步论证。Rasool等[101]研究发现番茄的果实产量、品质和水分利用效率均受灌溉、施肥和秸秆还田的影响；在较低的施氮肥和灌溉水平下，水稻秸秆还田较无秸秆处理番茄产量显著增加，可溶性糖量、糖酸比（SAR）和维生素 C（Vc）等指标均有所提升；但在较高的施氮肥和灌溉水平下，秸秆还田处理则会降低番茄产量，由此推断秸秆还田可以缓解有限灌溉水和氮肥造成的胁迫，从而提高温室种植番茄的果实产量和品质。该研究结论与张素瑜等[102]的研究结论有所矛盾。张素瑜等[102]研究表明在轻旱和水分适宜的土壤水分条件下，玉米秸秆还田可促进小麦根系生长，延长根系衰老时间，提升作物利用效率和产量；但土壤水分条件较差时，秸秆还田效果正好相反。这可能与作物种类、土壤质地和气候环境等因素有关。因此，秸秆还田应注意水肥条件的适用情况，达到正向增产效果。

4 秸秆还田产生的负面影响及防治措施

秸秆腐解缓慢和易诱发病虫害是当前秸秆还田实际生产应用时面临的主要难点问题，对农业种植及管理造成较大负面影响，导致农民对常规秸秆还田技术产生抗拒情绪，制约秸秆还田推广应用，亟须解决。

4.1 秸秆腐解缓慢及其防治措施

秸秆初期腐解缓慢，短时间内大量秸秆积聚，易超过土壤消纳能力，不仅加剧土壤空洞，影响后茬作物种子萌发与秧苗扎根，造成作物出苗率低、苗期根系虚浮等问题，影响作物产量；而且秸秆腐解养分释放与作物需求不匹配，造成秸秆营养元素利用率下降。

秸秆腐解的影响因素纷繁复杂，秸秆性质（碳氮比、碳磷比、木质素量等）、土壤性质（pH 值、通气性、养分状况、土壤温度、含水率等）、气候条件（温度、湿度、降雨量等）、还田模式（秸秆长度、还田量、耕作方式、秸秆埋深等）等均会对秸秆腐解速度造成一定影响[103-104]。当前，主要可通过充分粉碎秸秆、秸秆掩埋还田、秸秆氨化处理、加入促腐菌剂或腐熟剂等方式，促进秸秆腐解，加速秸秆养分释放。充分粉碎秸秆，尽可能减小秸秆长度，甚至秸秆粉末化还田，增大秸秆与土壤的接触面积，提高秸秆与土壤混合程度，加快水分吸收，加速营养物质溶解，为微生物代谢提供更多碳源和能量，促进微生物数量增长，提升秸秆腐解速度[105]。采用掩埋还田的秸秆腐解速度优于覆盖还田[106-107]，这可能是因为土壤中的湿度及夜间温度一般高于土壤表面，且秸秆隔层的保水保肥保墒的效果优于秸秆表层覆盖，从而更利于微生物的生长与繁殖，秸秆掩埋还田时腐解速度更快。氨化处理促使秸秆中由木质素、纤维素和半纤维素组成的三维网状大分子结构断裂成易发酵的小分子物质，并破坏秸秆细胞表层，加速秸秆腐解[108]；同时，氨化处理缓解土壤碳氮比失衡，有利于土壤微生物活动和生长繁殖，秸秆分解速度显著加快[109]。促腐菌剂和腐熟剂中富含一种或数种具有降解木质素、纤维素和半纤维素的真菌或细菌。真菌可穿透秸秆角质层进入秸秆缝隙，分泌水解酶降解纤维素等物质；细菌则通过分解小分子物质实现对有机物料的降解[110]。综上不难看出，秸秆腐解与微生物关系密切，秸秆腐解速度与微生物活性通常呈正相关关系。因此，可采取相关措施提高微生物数量及活性，加快秸秆腐解，解决秸秆还田土壤空洞和养分释放不及时的问题。

4.2 秸秆诱发病虫害及其防治措施

秸秆中存在病株残体且易携带病原菌和虫卵，直接还田易诱发或加剧农作物纹枯病、赤霉病、茎基腐病、大斑病等病害以及根结线虫、灰飞虱、潜叶蝇、负泥虫等虫害风险，加重土传病害[111-112]；此外，在干旱地区秸秆还田易造成农田鼠害，老鼠利用翻入土壤中的秸秆做窝，甚至作为过冬的食物，给来年的春播带来风险。

通过调整秸秆还田方式，可有效降低病虫害发生。研究表明，秸秆粉碎深翻相比于免耕覆盖，可显著降低玉米纹枯病和大斑病的发生程度[113]；秸秆作掩埋处理可有效地消灭病残体,减少田间菌源量，秸秆埋深超 20 cm 时二化螟等幼虫死亡率超过 60%[114]；充分粉碎秸秆至粉末状，能一定程度破坏秸秆中的虫卵和幼虫，有效降低虫害发生；采用秸秆堆沤还田方式，将秸秆预先进行堆肥、沤肥处理，腐熟后施入土壤，也可消灭大量寄生虫卵、病原菌及杂草草籽[115]。此外，秸秆添加生防菌还田可减少纹枯病等土传病害的发生[116]。通过引入芽孢杆菌、假单胞菌和菌根真菌等生防菌，改善土壤微生物群落结构，生防菌与病原菌竞争营养和空间，从而抑制病原菌的生长与繁殖；同时，生防菌还能提高作物提高抗病、抗虫性，降低病虫害的威胁[117]。

值得注意的是，无有害源的秸秆还田本身亦可有效抑制病虫害发生。秸秆还田后释放出酚酸物质，对病原菌产生化感作用，抑制玉米大斑病菌等菌丝生长，抑制玉米大斑病等病情指数的发展[118]。同时，秸秆还田改善土壤理化性质，增加土壤营养物质，一方面提升土壤中有益微生物多样性，与病原菌竞争养分，抑制病原菌生长繁殖[119]，另一方面改善土壤食物网结构，提高病原生物捕食者（蚯蚓、节肢动物等）的种类及数量，通过天敌捕食减少病虫害[120]。因此，在实际秸秆还田应用中，应加强秸秆有害源的控制，还田前尽可能减少秸秆中的病原菌和虫卵，从源头上降低秸秆还田病虫害的负面影响。

5 总结与展望

秸秆还田具有改良土壤理化性质、保水控盐和培肥增产等显著作用，对农业高效生产和环境可持续发展具有重要意义，值得推广应用。鉴于不同地区农业气候资源、土壤水肥气热条件和农业管理模式差别较大，在秸秆还田实际应用时应因地制宜，综合不同气候、土壤、秸秆、作物等多种因素，确定适宜的秸秆还田方式，提升秸秆还田效果。

秸秆还田对土壤改良及培肥增产的研究成果比较丰硕，但仍有许多问题有待进一步研究。例如：①秸秆腐解速度影响因素繁杂，气候条件、秸秆种类、土壤类型及水肥气热条件、土壤微生物种类及数量、秸秆埋深都会对其产生影响，研究各影响因素对秸秆腐解及其改良土壤、培肥增产的综合效应，探明秸秆腐解规律与土壤理化性质、作物生长、水肥利用等方面的内在联系及机理，进一步解决因腐解缓慢引起土壤空洞和养分释放不及时的问题。②秸秆还田技术尚可进一步优化。研究秸秆加工处理（如粉末化、氨化、碳化处理、堆沤肥处理等），添加相关药剂或微生物，调整秸秆还田、耕作方式或优化水肥管理等多种措施

复合作用下对土壤改良效果和作物生长及产量、品质的影响，探寻更优的秸秆还田技术，实现秸秆高效资源化利用。③研究不同气候区和种植习惯条件下，秸秆还田技术对不同类型、质地的土壤理化性质改善作用的差异，为不同地区的秸秆还田技术推广应用提供参考依据。④进一步探明秸秆还田对土壤各方面性质的影响规律及其作用机理，总结经验公式，构建应用模型，分析研究不同气候资源、土壤类型及水肥气热条件、种植作物品种和农业管理模式等条件下适宜的秸秆还田模式，选择还田量、埋深、耕作方式、水肥管理等指标参数，确定秸秆还田策略，指导实践农业生产，加快秸秆还田技术推广应用。

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The Effects of Straw Incorporation on Physicochemical Properties of Soil: A Review

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Abstract: Straw incorporation is a proven agronomic practice not only for improving water conservation and alleviating soil salinization but also increasing soil fertility and crop yield. This paper reviews the progresses in decades of studies on effects of straw incorporation on physical and biogeochemical properties of soil as well as the consequences for water and salt transport, soil nutrients and crop yield. We also review the side effects of straw incorporation and their mitigations. In particular, we focus on the combined effects of straw incorporation with other agronomic practices including tillage, soil conditioners, pretreatment of straw, and analyze the mechanisms underlying the changes in soil properties in response to these treatments. The effects of the amount of incorporated straw, its buried depth, the way of incorporation on water and salt movement are also analyzed. We discuss the mechanisms underlying the improved water storage and soil desalination, as well as soil fertility and crop yield due to straw incorporation. Several perspectives which deserve further studies are also highlighted, including its combined effect with nitrogen fertilization, accelerating straw decomposition, the impact on soil water and soil nutrients, as well as some detrimental influences and their mitigation. Based on available studies, some points worth attention in practical application of straw incorporation are addressed. This review provides a reference for research and application of straw in crop production.

Key words: straw incorporation; soil aggregation; soil water and salt movement; soil fertility; soil quality improvement

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