"粮食产业链数字化和创新技术研究"特约专栏文章之四

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印度尼西亚农业产业转型：利用新兴数字技术减少粮食损失（中英文）

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摘　要： 印度尼西亚的农业产业作为经济支柱，正面临物流效率低下、冷链基础设施不完善以及供应链分散等多重挑战，导致粮食损失与浪费（FLW）问题日益严重。据估算，FLW 已造成该国国内生产总值损失 4%~5%，不仅加剧了粮食不安全问题，还对环境造成了显著退化。针对这一困境，本文提出了一种创新的智能农业产业框架，该框架通过整合物联网（IoT）、人工智能（AI）、区块链、云计算等先进技术，致力于优化食品供应链绩效并显著减少 FLW。相较于传统方法，该框架能够实现食品供应链的实时监测、基于预测的分析以及全程可追溯性，为各利益相关方提供数据支持，有效应对供应链中的低效问题。为推动这一框架的实施，本文建议采取三阶段路线图：（1）在短期内针对高风险易腐商品开展试点项目；（2）在中期阶段扩展至岛际和多式联运物流体系；（3）在长期目标下，构建覆盖全国的食品物流 4.0 生态系统。通过这些数字技术手段，印度尼西亚有望向积极主动、数据驱动的农业产业转型，最大限度地减少粮食损失和环境影响。该模式不仅适用于印度尼西亚，还可为其他面临类似粮食安全挑战的发展中国家提供参考，助力全球向更高效、可持续的食品系统迈进。

关键词： 食品物流；印度尼西亚；实时监测；供应链；可持续性

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Transforming Agroindustry in Indonesia: Emerging Digital Technologies for Reducing Food Loss(Chinese and English versions)

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Abstract: Indonesia's agroindustry is an economic pillar but is hampered by high food loss and waste (FLW) caused by inefficient logistics, inadequate cold chain infrastructure, and fragmented supply chains. FLW leads to economic losses of 4%~5% of Indonesian GDP, further leading to food insecurity and environmental degradation. This paper proposes a Smart Agroindustry Framework that integrates the Internet of Things (IoT), Artificial Intelligence (AI), Blockchain, and Cloud Computing to optimize food supply chain performance and reduce FLW. Compared to conventional methods, this approach offers real-time monitoring, forecast-based analysis, and traceability to support stakeholder decisions and counter inefficiencies in the supply chain. The three-stage recommended road map comprises: (1) short-term: pilot implementations targeting high-risk perishable commodities, (2) medium-term: expansion into inter-island and multi-modal logistics, and (3) long-term: Nationwide implementation of a Food Logistics 4.0 ecosystem. Through these digital technology approaches, Indonesia has the potential to transition towards a proactive, data-enabled agroindustry that minimises losses and environmental footprints. Beyond Indonesia, this model is adaptable for other developing nations facing similar food security challenges, reinforcing the global movement towards more efficient and sustainable food systems.

Key words: food logistics; Indonesia; real-time monitoring; supply chain; sustainability

印度尼西亚作为全球生物多样性排名第二的国家，其农产品贸易领域蕴藏着巨大的发展潜力[1-2]。农业产业作为该国经济的重要支柱，通过紧密相连的价值链将农业生产、生鲜处理、加工产业与终端消费市场有机衔接[3]。然而，作为一个由 2 300 多个有人居住岛屿组成的群岛国家，印度尼西亚面临着严峻的食品物流挑战，导致大量粮食损失与浪费。统计数据显示，2000—2019 年间，该国每年产生的食物垃圾高达 2 300 万至 4 800 万 t，相当于每人每年浪费 115~184 kg 的食物。这一数字背后意味着，原本可为 6 100 万~1.25 亿人（约占印度尼西亚人口的 29%~47%）提供食物的资源白白流失[4]。

粮食损失与浪费造成的经济影响十分深远。联合国粮食及农业组织（Food and agriculture organization of the United Nations，FAO）估计，

2021 年全球因食物损失造成的经济损失约为 4 000 亿美元，这一数字还不包括家庭、零售商、餐馆和其他食品服务部门浪费的食物。根据联合国环境规划署的数据，全球每年因食物浪费造成的经济损失超过 1 万亿美元。这一金额几乎相当于印度尼西亚、土耳其和荷兰等国的国内生产总值总和[5-7]。具体而言，印度尼西亚每年因粮食损失与浪费造成的经济损失估计在 136.4~352.9 万亿印尼盾之间，相当于该国国内生产总值的 4%~5%[8]。深入理解粮食损失的关键环节及其成因，将为我们在技术、政策、社会经济和战略层面制定有效的预防和减少损失的策略提供重要依据。

至于因印度尼西亚地理状况导致的物流挑战，联合国粮食及农业组织列举了几个造成粮食损失与浪费的因素[4]。首先，农产品产量过剩、市场体系运行效率低下以及实时数据获取能力不足，导致了资源分配的严重失衡。这种失衡使得部分区域出现产品过剩而造成浪费，同时其他地区却面临供应短缺的问题。其次，技术装备和基础设施的局限性，严重影响了供应链各环节的作业效率，尤其是在分拣、清洗和包装等关键环节，不仅效率低下，而且难以实现对产品质量的有效监控。此外，在配送环节，由于缺乏实时监控，产品在运输过程中可能面临多重风险。具体而言，环境条件的变化、反复装卸操作等因素，都可能对产品的质量和数量造成负面影响[9]。

应对这些挑战需要创新的解决方案。尽管印度尼西亚一直在努力改善食品物流和供应链，但现有解决方案仍较为零散、被动且效率低下。传统的冷链管理和配送系统由于缺乏实时监测、预测分析以及数据驱动的决策机制，难以有效控制食品变质和供应链中断问题[10-12]。尽管已有研究分别探讨了物联网、人工智能、区块链、云计算等技术在供应链管理中的应用潜力，但目前尚未形成一个能够将这些技术协同整合的综合框架，以系统性地从多层面减少粮食损失与浪费。本研究通过提出智能农业产业框架，填补了这一研究空白。该框架旨在通过主动加强食品质量控制、提高物流效率并增强供应链透明度，实现食品供应链的全面优化。与传统方法不同，该框架能够实现实时干预、自动风险检测以及区块链保障的可追溯性，从而确保食品从农场到消费者手中的全程质量可控。通过实施这一全面的、技术驱动的创新模式，印度尼西亚不仅能够从被动的损失管理转向主动的、数据驱动的农业产业管理，还将为其他面临类似挑战的发展中经济体提供可持续食品物流的示范方案。

物联网（Internet of things，IoT）设备与机器学习（Machine learning，ML）算法的深度融合，为食品物流 4.0 系统提供了实时质量监测和预测能力，有效预防和减轻运输过程中的潜在损失[13]。基于物联网和区块链的技术体系构建了透明化的数据管理和流程控制系统，为食品配送决策提供了有力支持[14]。大数据分析和人工智能（Artificial intelligence，AI）凭借其强大的计算能力，能够有效处理来自物联网传感器的复杂数据，从而优化数据驱动的运输规划和物流管理[15]。此外，大数据、云计算和物联网的协同应用为各利益相关方提供了高效的协同物流配送调度手段[16]。

通过利用这些技术，印度尼西亚能够从传统的被动应对方式，转变为智能、主动的系统，加强决策制定、提高粮食安全、最大限度减少粮食损失与浪费，并最终降低对环境的影响。本研究提出了一套系统性框架，旨在通过整合物联网、机器学习及其他先进数字技术以优化食品物流网络，有效减少印度尼西亚食品供应链中的资源浪费，从而推动实现可持续发展。

1 文献综述

1.1 农业产业与食品供应链面临的挑战

农业产业是以植物和动物为主要原料进行产品生产的产业。从更广泛的视角来看，农业产业是一个相互关联的价值链体系，涵盖了从种植与养殖（上游）、加工与制造（中游）到市场与消费（下游）的完整链条。该产业的目标是通过加工处理，将投入转化为具有更优良特性的产出。农业产业不仅是印尼经济增长的关键驱动力，还为农村地区提供了大量就业机会，支持了当地居民的生计，并通过增值加工和出口活动为国民收入做出了重要贡献。随着农业产业化工程的不断推

进和改进，农业产业的市场拓展也日益扩大，物流活动规模也随之显著增长[3,17-19]。

食品物流是一个复杂的过程，涉及多个运输和装卸环节。食品物流流程通常始于生产商和供应商，产品在此完成装箱后，通过公路、铁路、海运或空运等多种运输方式，最终送达终端客户[20-21]。印度尼西亚的食品物流系统面临严峻挑战，这主要源于其独特的地理特征和基础设施状况。该国的群岛地理特征决定了其物流体系必须依赖多式联运网络，涵盖陆路、海路和空运等多种运输方式。这种复杂的物流体系往往导致供应链分散和基础设施不完善，从而引发效率低下问题，最终影响易腐货物的质量和供应[11,14,22]。此外，从上游到下游的物流流程缺乏一个集成化的物流平台，这也是导致效率低下问题的重要原因[23]。这些效率低下问题不仅增加了食品物流的经济成本，也带来了显著的环境负担[24]。

食品物流的效率高度依赖于多式联运的运作，而这一过程受到燃料成本、基础设施状况和运输方式可及性等因素的显著影响[25]。研究表明，道路维护不足或港口拥堵等问题会导致运输延误和成本上升[21]。在食品供应链中，易腐农产品尤其容易受到运输过程中的质量损失影响。温度波动和操作失误会加速产品腐烂变质，造成显著的经济损失[26-27]。一项最新研究指出，缺乏完善的冷链系统会导致水果和蔬菜等易腐农产品在到达消费者之前就发生变质，这凸显了优化物流体系和基础设施的紧迫性[28-29]。这些问题不仅增加了经济成本，还加剧了食物浪费和碳排放，对环境造成负面影响[29]。

供应链的每个阶段都给参与者和利益相关者带来挑战。管理多个生产商和供应商（如农民 A、B 和 C，或供应商 D、E 和 F）并确保产品同步装入集装箱是一项重大挑战[30]。生产商和供应商阶段的延误或沟通不畅可能会扰乱整个物流流程[15]。

与普通货物相比，食品具有易腐性特征，在运输过程中对环境条件的要求更为严格。研究表明，集装箱内若缺乏适当的制冷或温度控制，可能导致食品品质下降甚至变质，造成显著的经济损失[31]。此外，在集装箱装卸环节，操作不当可能对食品造成物理性损坏[32]。为确保食品质量，业界普遍建议采取安全包装措施、规范叉车操作流程以及优化装载技术[16,24,33-34]。

食品物流行业必须严格遵循卫生、安全和可追溯性方面的严格规定。特别是在跨境运输过程中，企业需要应对不同国家的进出口法规要求，这可能造成运输延误并增加文书处理工作量。出口国与进口国之间的法规差异和标准不一致可能引发显著的粮食损失与浪费问题，例如，不符合进口国标准的食品可能被迫销毁或以倾销方式进入供应过剩的本地市场[35]。物流流程的最终环节是将货物配送至终端客户，包括食品加工厂、零售商和消费者。最后一公里配送通常面临成本高昂且时间紧迫的双重挑战，因此需要建立高效可靠的路线规划和配送网络，以确保食品能够新鲜、准时地送达客户手中[36]。

最后，我们必须认识到食品物流在运输过程中因燃料消耗会产生显著的碳足迹。为了减少对环境的影响，采取优化供应链路线和使用节能运输方式等可持续措施至关重要[15]。在衡量环境影响时，除了关注食品生产和碳足迹外，还应同等重视粮食损失与浪费的数量。据估算，损失和浪费的食品所产生的碳足迹高达 33 亿 t 二氧化碳[37-38]。

1.2 食品供应链中的先进数字技术

在探讨工业 4.0 中的先进数字技术时，有几个关键术语尽管广为人知，但其具体作用和应用场景可能并不为所有非专业人士所熟知。IoT 作为工业 4.0 的核心技术之一，通过互连设备实现物理环境数据的实时采集、传输与分析[39-40]。AI 则在数据处理与分析领域发挥着关键作用，能够通过机器学习算法进行智能决策和预测[21]。区块链技术通过去中心化的分布式账本，确保数据交易和变更的安全性与透明性[24]。大数据技术专注于海量数据的高效存储、处理与分析，为工业 4.0 提供数据驱动的决策支持[41-42]。云计算则通过互联网提供弹性扩展的计算资源，支持数据存储与计算任务的高效执行[16,34]。简而言之，物联网负责感知与数据采集，人工智能承担智能决策与预测，区块链确保数据安全与可信度，大数据

技术实现海量数据的高效管理，而云计算则为整个系统的运行提供弹性化的基础设施支持。这些技术的协同作用构成了工业 4.0 的数字化转型基础。

为了优化食品物流并减少食品损失，物联网、人工智能、区块链和云计算的整合提供了一个全面的数字解决方案。每项技术都为提高供应链效率发挥着独特作用（见表 1）。

表 1 农业产业中减少粮食损失的关键数字技术

Table 1 Key digital technologies for food loss reduction in agroindustry

技术	在食品物流中的作用	主要优势	挑战	参考文献
物联网（IoT）	（通过传感器、控制器和执行器）对环境条件进行实时监控	防止食品变质，改进追踪，增强冷链完整性	实施成本高，偏远地区存在连接问题	[43-45]
人工智能（AI）与机器学习（ML）	食品变质的预测分析、供需预测	减少浪费，优化运输，提升决策能力	需要大量数据集，集成复杂	[12-13,46]
区块链	食品供应链安全、防篡改的可追溯性	提高透明度，减少欺诈，确保食品安全	可扩展性，监管障碍	[47-50]
云计算	集中式数据管理，提供可扩展存储，并支持实时数据处理与决策	实现跨利益相关方协作，增强分析能力	数据安全，依赖稳定的互联网基础设施	[16,34,50]

ML 方法和算法已发展成熟，可根据具体需求从现有数据中进行合理选择。K 均值聚类算法作为一种经典的无监督学习方法，展现出高效处理大规模数据集的能力。该算法通过衡量数据相似性将数据划分为不同簇，从而实现新的分类。值得注意的是，K 均值聚类不仅能够依据多个参数准确划分食品质量等级，还能提供精确且易于理解的分类结果[51-53]。此外，先进的聚类方法在水果成熟度分类方面也展现出显著优势，为相关方确定发货优先级、减少变质损失提供了有力支持[54]。在有监督学习领域，深度学习技术表现尤为突出，其在预测水果成熟阶段时的准确率已超过 95%，为优化物流规划提供了可靠依据[55-56]。

ML 模型不仅能够预测食品质量，还能够检测食品污染和掺假情况。通过分析传感器数据，这些模型能够识别异常情况，从而迅速采取干预措施，防止问题产品流入市场。这对保障食品安全标准和公众健康具有重要意义。总体而言，机器学习在食品质量预测方面的应用，不仅提升了对易腐食品的管理能力，还减少了浪费，提高了产品质量，并优化了供应链运营效率[41,57-58]。

IoT 与 ML 相互结合，借助云计算提供的强大可扩展存储和计算能力，为需求预测和库存管理领域带来了革新性的解决方案。通过将人工智能算法与物联网设备采集的实时数据相结合，并辅以历史销售数据进行深入分析，企业能够精准预测未来的需求模式。这种前瞻性的预测能力使企业得以动态调整库存水平，有效规避库存积压或供应短缺的风险，从而实现资源的最优配置[57,59]。

区块链技术因其能够在整个供应链中优化数据管理、安全性和可追溯性，正逐渐被视为食品物流现代化的关键技术。研究表明，区块链能够有效记录运输过程中的冷链完整性，确保数据的可验证性[47-48]。与此同时，云平台通过提供集中化的数据和应用访问，不仅支持各利益相关方的协同合作，还显著提升了供应链的整体协调性和运营效率[49-50]。这种技术组合不仅增强了供应链的透明度，还为食品物流的智能化转型提供了坚实的技术支撑。

尽管 IoT、AI、区块链、云计算等技术具有彻底革新食品物流的潜力，但其广泛应用仍面临多重障碍。首先，高昂的基础设施投资成本，尤其是物联网传感器和云存储设施的投入，给小型农户和物流服务商构成了显著的经济负担[16]。其次，印度尼西亚偏远地区普遍存在的网络连接障碍可能干扰实时数据传输，从而削弱智能监测系统的效能[22]。此外，基于区块链的可追溯性监管体系尚未成熟，这为跨境食品贸易的合规性和监管一致性带来了不确定性[60]。更为关键的是，人工智能和预测分析技术依赖于海量的历史数据支持，而农业产业链各环节普遍存在的零散数据记录方式导致数据获取障碍[61]。要有效应对这些挑

战，需要政府机构、私营部门和科技供应商等多方利益相关者开展协同合作，通过制定扶持政策、优化数字基础设施和推动行业标准化等措施，共同促进这些创新技术的普及应用[62]。

2 智能农业产业的拟议框架

食品物流 4.0 的出现，标志着食品供应链管理领域的重大变革，它强调通过整合先进技术来提高效率、透明度与可持续性。拟议框架充分利用了新兴先进数字技术的协同能力。

2.1 智能农业产业的设计与开发

设计一个强大的智能农业产业框架，需要采用结构化方法，整合多项技术，以提升效率、可追溯性和可持续性。鉴于现代农业产业系统的复杂性，思维导图成为一种至关重要的工具，可用于可视化关键组成部分。通过梳理 IoT、AI、区块链、云计算等核心要素，思维导图有助于明确各部分作用、确定工作内容，并确保形成一个连贯的实施策略。这种结构化呈现方式，有助于设计出面向未来的农业产业生态系统（图 1）。

智能农业产业的设计与开发，涉及将数字技术无缝融入农业生产实践与食品物流之中[63]。这种融合旨在打造一个能实时监控与决策、响应迅速且适应性强的供应链。设计中的 IoT、AI、区块链以及云计算，能够有效应对农业产业和食品物流中固有的多方面挑战。这些技术的协同应用，构建了一个集成化的系统框架，将技术堆栈的工作流程实现可视化（如图 2 所示）。

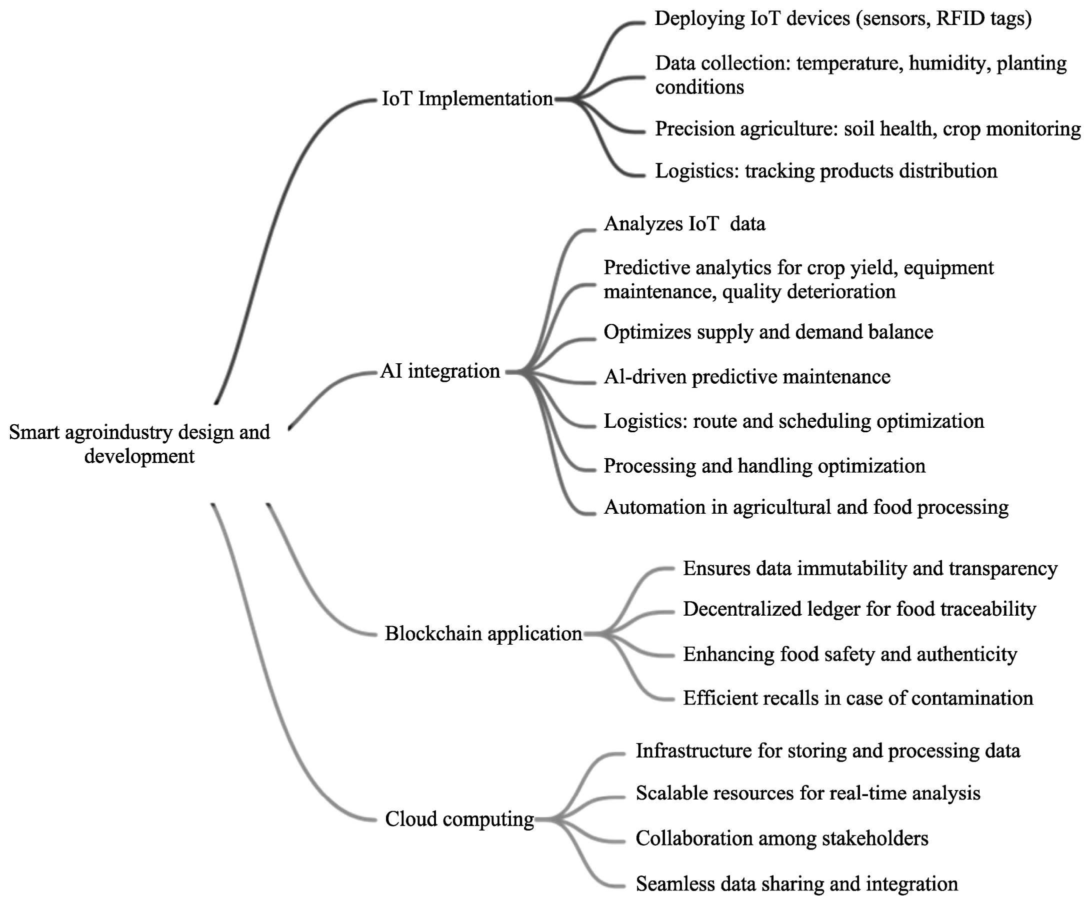

图 1 智能农业产业设计与开发思维导图

Fig.1 The mindmap of smart agroindustry design and development

区块链技术与物联网设备的融合能够显著提升食品供应链的可追溯性与透明度。具体而言，物联网设备实时采集多维度参数数据，随后将这些信息存储于区块链平台，构建一个不可篡改的分布式账本，供相关方追溯与验证食品的真实性和状态。穆杜德等[64]提出了一种创新的物联网-区块链架构，通过部署预言机和智能合约，有效提升了数据可靠性并实现了供应链流程的自动化。

AI 可通过管理和精简区块链数据以优化性能，显著提升区块链系统的运行效率和性能表现。

研究表明，在基于人工智能的区块链解决方案中，引入 BDI（Belief，desire，intention，信念、愿望与意图）智能体模型，能够有效提升供应链管理的智能化水平和系统性能。这种创新性架构不仅能够实现对区块链数据的智能处理与分析，还能确保系统具备高度的适应性和可扩展性，从而更好地满足食品物流领域不断变化的实际需求[48]。

物联网与人工智能的深度融合，通过实现高效实时数据处理与智能决策支持，在食品物流优化领域发挥着至关重要的作用。具体而言，物联网设备能够全天候采集食品物流过程中的各项关键数据，确保食品在运输过程中的安全性和品质稳定性。与此同时，人工智能技术通过对海量数据的高效处理，能够识别数据中的潜在模式、预测可能的供应链风险，并为物流运作提供智能化优化建议。基于人工智能的深度分析，系统能够为供应链管理者提供精准的效率评估洞察，有效减少食品损耗，同时通过智能路径规划优化运输路线。这些技术手段的综合应用，为决策者提供科学依据，从而显著提升决策水平[65]。

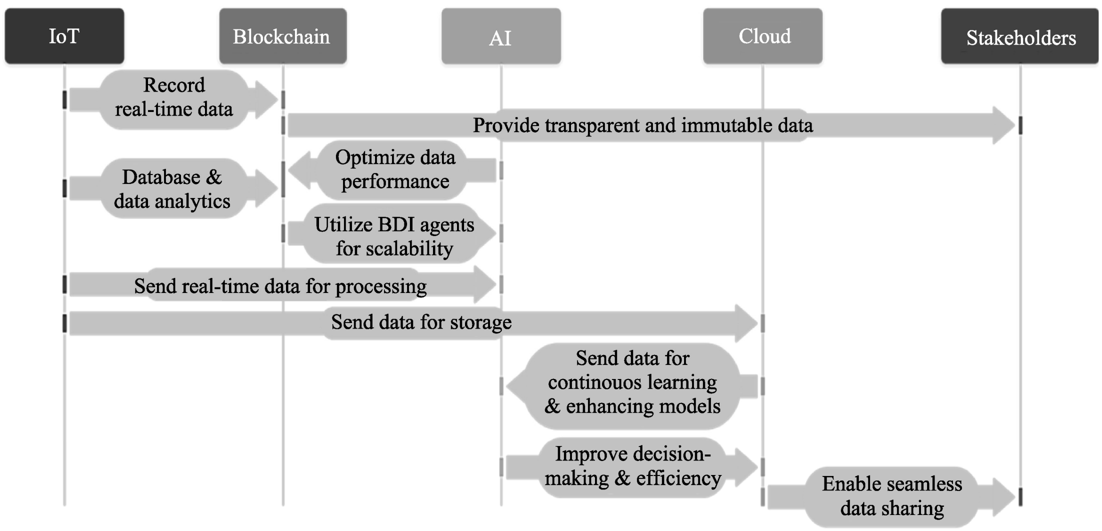

图 2 系统集成框架

Fig.2 System integration framework

这些技术的融合推动形成了一种高效、透明且具备高度韧性的智能农业产业模式，使其能够灵活适应动态变化的市场需求和复杂多变的环境条件。然而，尽管技术融合带来了显著优势，但仍面临诸多挑战，包括数据互操作性障碍、系统安全隐患以及标准化需求等问题。为确保不同系统和设备间的有效通信，亟需建立统一的技术标准与协议框架[21]。同时，数据安全与隐私保护至关重要，特别是在处理涉及食品安全和质量的敏感信息时，必须采取严格的安全措施[66-67]。解决这些挑战需要多方利益相关者的协同合作，包括技术开发者、农业从业者、食品行业专家以及监管机构等[62]。

2.2 应用路线图

拟议的智能农业产业框架遵循一个分三个阶段的结构化路线图：短期、中期和长期实施阶段。每个阶段都在技术集成、基础设施扩展和政策支持的基础上逐步推进，以确保物联网、人工智能、区块链和云计算在食品供应链中得到可持续且可扩展的应用（图 3）。时间跨度为 5 年的发展期，从试点项目到全国范围的实施（表 2）。

2.2.1 短期实施：试点项目与可行性研究

路线图的第一阶段重点开展针对高价值易腐商品（如辣椒、芒果、牛肉、海鲜和乳制品）的试点项目。这些商品之所以被选中，是因为它们不仅具有较高的经济价值，而且在运输过程中容易腐坏。在存储设施和运输车辆中安装了温度和湿度传感器以及 GPS 追踪器等物联网设备，用于实时采集环境数据。随后，通过机器学习模型对这些数据进行分析，以实现产品成熟度

预测、冷链运输完整性监测以及潜在腐坏风险评估[13]。

为了确保向数字化物流的平稳转型，为供应链中的各个参与者——包括农民、经销商以及仓库经理——量身定制的培训项目必不可少。这些培训项目将聚焦于物联网设备的操作、人工智能预测结果的解读，以及区块链可追溯系统的有效实施。在此关键阶段，我们的核心目标是在大规模推广与实施之前，展示技术集成在提升供应链效率与经济效益方面的巨大潜力与可行性。

2.2.2 中期实施：扩展至多样化商品与综合多式联运的物流体系

一旦试点项目圆满达成预期成效，该框架将进一步拓展，惠及高价值作物以外的广泛农业领域。此扩展阶段将聚焦于将物联网技术与基于人工智能的物流网络深度融合至岛际供应链体系之中，旨在强化对偏远且基础设施薄弱地区的实时、高效监控能力。中期愿景聚焦于通过研发专为中小企业量身定制、兼具成本效益与高度可扩展性的数字技术解决方案，以提升其在该领域的采纳与应用水平。在此过程中，政策层面的有力介入——涵盖政府激励政策、税收优惠措施以及数字基础设施的战略投资——将发挥核心作用，确保这些前沿技术能够广泛普及，惠及更广泛的农业参与者。

2.2.3 长期实施：全国范围采用与智能物流生态系统

最终阶段将聚焦于实现全国范围内的广泛应用，致力于将印度尼西亚的食品供应链全面升级为一个无缝集成的智能供应链生态系统。此阶段的关键在于携手地方政府、行业伙伴及国际组织，共同制定统一的物联网与人工智能相关法规标准。

为推动这一全国性的数字化转型进程，我们将精心策划资金援助模式，为小农户和中小企业提供技术采纳补贴，确保转型过程的包容性与公平性。同时，我们还将积极展望并探索前沿科技，如 5G 物联网设备、人工智能赋能的机器人自动化以及量子计算驱动的物流优化方案等，旨在进一步增强供应链的灵活性与韧性。

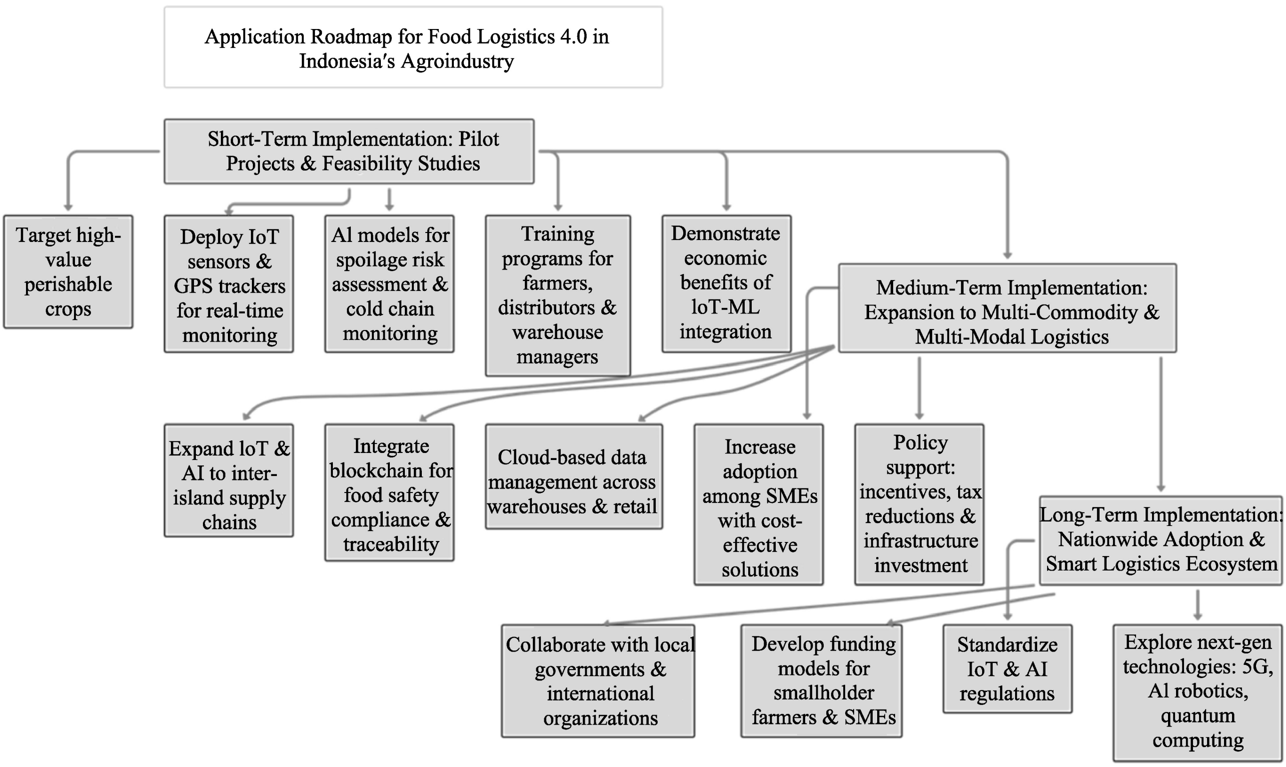

图 3 智能农业产业技术堆栈实施路线图

Fig.3 Roadmap for technology stack implementation in smart agroindustry

表 2 印度尼西亚智能农业产业三阶段路线图及实施时间表

Table 2 Three-phase roadmap and implementation timeline for smart agroindustry in Indonesia

技术/行动	关键行动	预期成果	第一阶段（1~2 年）	第二阶段（2~4 年）	第三阶段（4~5 年）	挑战与解决方案
物联网实施	在高风险易腐商品（蔬菜和水果、肉类和海鲜、乳制品）中部署物联网传感器	改善冷链监测，减少腐坏	在关键地区进行试点部署	扩展至多商品供应链	在农业产业物流中全国推广	**挑战**：成本高、连接性问题 **解决方案**：公私合作、政府激励、基础设施升级
人工智能与预测分析	运用人工智能模型进行腐坏风险和需求预测	优化库存，减少浪费	利用人工智能进行腐坏风险评估	基于人工智能的需求预测	基于人工智能的自动化与机器人技术	**挑战**：需要大量数据集；进行培训 **解决方案**：数据共享框架、人工智能培训项目
区块链溯源	安全的食品追踪与食品安全合规	提高透明度，减少欺诈	–	小规模集成用于溯源	全国性区块链溯源	**挑战**：可扩展性、监管不确定性 **解决方案**：政策制定、行业合作
云计算整合	实时数据共享与分析	加快决策速度，改善协调	–	基于云的供应链平台	全面的国家级云基础设	**挑战**：数据安全、对稳定网络的依赖 **解决方案**：网络安全政策、公私合营投资
培训与能力建设	提升利益相关者的数字素养与技术应用能力	提高技术应用率和效率	为农民和物流供应商提供培训	将业务拓展至中小企业及岛际物流领域	开展全国性数字素养项目	**挑战**：对变革的抵触、技能差距 **解决方案**：激励措施、全国性培训计划
政策与监管框架	针对智慧农业产业的数字治理	制定智慧食品物流的标准化法律框架	–	起草可追溯性相关法规	实现食品物流4.0的全面法律标准化	**挑战**：政策采纳缓慢、执法问题 **解决方案**：多方利益相关者合作、监管改革

3 结论与建议

鉴于印度尼西亚农业产业长期面临食品损失和浪费（FLW）问题，其主要原因包括物流体系效率低下、农业基础设施建设滞后以及缺乏实时数据整合能力。针对这一挑战，本研究提出了一套创新的智能农业产业框架，该框架通过整合物联网（IoT）、人工智能（AI）、区块链技术、云计算等先进信息技术，致力于构建高效、可持续的食品供应链体系。为确保该框架的有效实施，我们设计了一个系统化的三阶段、5 年的实施路线图，旨在通过试点项目的逐步推广，最终实现全国范围内的广泛应用。该方案特别关注并致力于解决当前存在的基础设施限制、政策法规空白以及利益相关者准备程度不一等关键性挑战。通过这些技术的协同应用，印度尼西亚不仅能够显著减少农业经济损失，提升粮食安全保障水平，同时还能将农业活动对环境的影响降至最低，从而为其他发展中国家提供可借鉴的实践经验与示范效应。

为了确保印度尼西亚食品供应链智能化转型的成功实施，印度尼西亚必须优先投资于数字基础设施建设、强化政策支持体系，并推动多方利益相关者的深度合作。在转型初期，对冷链物流体系、基于区块链的溯源系统以及人工智能分析技术的投入至关重要，这些基础设施将为优化食品配送网络奠定坚实基础。同时，针对农民群体和供应链管理者的能力建设项目也应同步推进，这不仅有助于提升技术应用水平，更能确保转型成果的可持续性。通过采取协调一致的技术驱动型策略,印度尼西亚有望构建一个具备高度韧性的数据驱动型农业产业体系,在有效减少食物浪费的同时，实现经济与环境的双重可持续发展目标。

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Transforming Agroindustry in Indonesia: Emerging Digital Technologies for Reducing Food Loss (英文原文)

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Abstract: Indonesia's agroindustry is an economic pillar, yet it is hindered by high food loss and waste (FLW) due to inefficient logistics, inadequate cold chain infrastructure, and fragmented supply chains. FLW leads to economic losses equivalent of 4%~5% of Indonesian GDP, exacerbating food insecurity and environmental degradation. This paper proposes a Smart Agroindustry Framework that integrates the Internet of Things (IoT), Artificial Intelligence (AI), Blockchain, and Cloud Computing to optimize food supply chain performance and reduce FLW. Compared to traditional methods, this approach offers real-time monitoring, forecast-based analysis, and traceability to support stakeholder decisions and counter inefficiencies in the supply chain. The recommended three-stage road map includes: (1) short-term: pilot implementations targeting high-risk perishable commodities, (2) medium-term: expansion into inter-island and multi-modal logistics, and (3) long-term: nationwide implementation of a Food Logistics 4.0 ecosystem. By leveraging these digital technologies, Indonesia can transition to a proactive, data-enabled agroindustry that minimizes losses and environmental impact. This model is also adaptable for other developing countries facing similar food security challenges, supporting the global shift towards more efficient and sustainable food systems.

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Indonesia, the world's second most biodiverse country[1-2], has great potential in agricultural trade. Its agroindustry serves as a critical economic engine in the country, connecting farming, post-harvest handling, processing industries, and distribution through the interconnected value chain [3]. However, as an archipelagic nation with more than 2,300 populated islands and a population of over 282 million, Indonesia faces significant challenges in its food logistics systems, leading to substantial food loss and waste (FLW). The nation produced between 23 and 48 million tonnes of food waste annually between 2000 and 2019, which is equivalent to 115 to 184 kg per person annually. This level of FLW could have provided sustenance for 61–125 million people, or about 29–47% of Indonesia's population [4].

The economic impact of FLW is staggering. FAO estimates that the economic value of lost food is approximately 400 billion USD in 2021, not including the food wasted by households, retailers, restaurants, and other food services, which according to UNEP costs the global economy over USD 1 trillion annually[5-6]. This amount is almost equivalent to the GDP of countries like Indonesia, Türkiye, and the Netherlands[7]. The estimated economic loss resulting from food loss and waste in Indonesia ranges from USD 13.64 trillion to USD 35.29 trillion per year, equivalent to 4 to 5 per cent of the country's GDP[8]. Identifying key loss points and their causes is critical to implementing mitigation strategies at the technical, policy, socioeconomic, and strategic levels.

Regarding logistics challenges due to Indonesia's geographical situation, FAO[4] listed several factors contributing to FLW. Overproduction occurrences, inefficient market systems, and lack of real-time data hinder effective distribution, causing surplus waste in some areas and shortages in others. The limited technology and infrastructure result in inefficient sorting, cleaning, and packaging and unmonitored product quality along the supply chain. The distribution process is the longest time that the products go unmonitored, during which activities can negatively influence the quality (and quantity) during transportation. Environmental conditions may experience changes, and repetitive handling and moving may damage the products[9].

Addressing these challenges demands innovative, coordinated solutions. Although efforts to improve food logistics and supply chain efficiency in Indonesia are ongoing, current approaches fragmented, reactive, and inefficient. Traditional cold chain management and distribution systems lack real-time monitoring, predictive analytics, and data-driven decision-making, resulting in uncontrolled food deterioration and supply chain disruptions[10-12]. Previous studies have explored isolated applications of IoT, AI, Blockchain, and Cloud Computing, but no integrated framework synergises these technologies to systematically reduce food loss and waste (FLW) at multiple supply chain levels. This study bridges that gap by introducing a Smart Agroindustry Framework designed to proactively enhance food quality control, logistics efficiency, and supply chain transparency. Unlike traditional approaches, this framework enables real-time intervention, automated risk detection, and blockchain-secured traceability, ensuring that food products maintain quality from farm to consumer. By implementing this holistic, technology-driven model, Indonesia can transition from reactive loss management to proactive, data-driven agroindustry, setting a precedent for sustainable food logistics in other developing economies facing similar challenges.

The integration of Internet of Things (IoT) devices and Machine Learning (ML) algorithms offers real-time quality monitoring and prediction capacity in the Food Logistics 4.0 system, allowing prevention and mitigation of losses that may occur during long-distance transportation[13]. IoT-based and Blockchain technologies support transparent data management and process control to support decision-making in food distribution[14]. Big Data analytics and Artificial Intelligence (AI) possess advanced computational powers to process highly complex data from IoT sensors, improving data-driven transportation planning and logistics optimisation[15]. Moreover, the incorporation of Big Data, Cloud Computing, and IoT is an effective method for cooperative logistics delivery scheduling across stakeholders[16].

By leveraging these technologies, Indonesia can transition from traditional reactive approaches to intelligent, proactive systems that enhance decision-making, improve food security, minimise food loss and waste, and ultimately reduce environmental impact. This study proposes a comprehensive framework integrating IoT, ML, and other advanced digital technology to optimise food logistics, aiming to reduce FLW and promote sustainability within Indonesia's food supply chains.

1 LITERATURE REVIEW

1.1 Agroindustry and Food Supply Chain Challenges

Agroindustry is an industry that produces products using main components derived from plants and animals. In the broader context, agroindustry is an inter-related value chain from farming (upstream) to the processing industry (middle-stream) and to end customers (downstream). The objective of agroindustry is to convert input(s) by applying processes into output(s) that have much better properties or characteristics compared to the input(s). The agro-industry sector is a crucial driver of economic growth in Indonesia, providing employment opportunities, supporting rural livelihoods, and contributing to national income through value-added processing and exports. The more available and improved agro-industrial engineering has encouraged agroindustry to expand its market, leading logistics activities to become more massive[3,17-19].

Food logistics is a multifaceted process involving multiple transportation and handling stages, starting from producers and suppliers, where products are loaded into containers and transported via road, rail, sea, or air before reaching the final customers[20-21]. Indonesia's food logistics system faces significant challenges, particularly due to its unique geographical and infrastructural context. The nation's archipelagic structure necessitates complex, multimodal transportation networks encompassing land, sea, and air routes. This complexity often leads to fragmented supply chains and inadequate infrastructure, resulting in inefficiencies that affect the quality and availability of perishable goods[11,14,22]. The absence of an integrated logistics platform from upstream to downstream processes contributes to these inefficiencies, which in turn increases the economic and environmental costs of food logistics[23-24].

Food logistics often relies on the efficiency of multimodal transportation modes, which depends on fuel costs, infrastructure conditions, and availability of transport options[25]. Poorly maintained roads or congested shipping ports can lead to delays and increased costs[21]. Perishable agricultural products are specifically susceptible to quality degradation during transit. Temperature fluctuations and improper handling can accelerate spoilage, leading to significant economic losses[26-27]. A study highlighted that without adequate cold chain systems, perishable agricultural products like fruits and vegetables often spoil before reaching consumers, underscoring the critical need for improved logistics and infrastructure [28-29]. These inefficiencies not only increase economic costs but also have environmental implications due to increased food waste and higher carbon emissions from prolonged transportation [29].

Each stage of the supply chain bears challenges for the actors and stakeholders. Managing multiple producers and suppliers (such as Farmers A, B, and C or Suppliers D, E, and F) and ensuring synchronised loading of products into containers is a significant challenge[30]. Delays or miscommunication at the producers' and suppliers’ stages can disrupt the entire logistics process[15].

Unlike general cargo, food products are often perishable and require controlled environments during transit. The lack of proper refrigeration or temperature control in containers can result in spoilage, leading to significant losses[31]. During the container loading and unloading process, improper handling can lead to damaged food products[32]. Ensuring safe packaging, effective use of forklifts, and optimised loading techniques are crucial to maintaining product quality[16,24,33-34].

Food logistics must also adhere to strict regulations regarding hygiene, safety, and traceability. Cross-border shipments, in particular, require compliance with different countries' import/export regulations, which can cause delays and increased paperwork. The differences in regulations and standards between exporting and importing countries can lead to FLW, e.g., non-compliant foods are thrown away or dumped on a sufficiently provided local market[35]. The final stage of the logistics flow involves distributing goods to customers, including food processing factories or retailers and end consumers. Last-mile delivery is often costly and time-sensitive, requiring efficient route planning and distribution networks to ensure food reaches customers fresh and on time[36].

Finally, it is important to acknowledge that food logistics generates a considerable carbon footprint due to fuel consumption in transportation. Sustainable practices, such as optimizing supply chain routes and using energy-efficient transport modes, are necessary to reduce environmental impact[15]. The measurement of environmental impact has to consider not only the food production and carbon footprint but also the volume of FLW. The carbon footprint of lost and wasted food was estimated to reach up to 3.3 giga tonnes of CO_2 [37-38].

1.2 Advanced Digital Technology in Food Supply Chain

When discussing advanced digital technology, there are several terms that, although popular, not all laypeople understand their roles in Industry 4.0. The Internet of Things (IoT) enables interconnected devices to collect data from the physical environment[39-40]. Artificial Intelligence (AI) processes and analyses the data to make intelligent decisions and predictions[21]. Blockchain securely stores and verifies transactions or data changes in a decentralised ledger[24]. Big Data refers to large volumes of data that require advanced methods to store, process, and analyse[41-42]. Cloud Computing provides scalable resources and services over the Internet for data storage and computation[16,34]. In short, IoT is for sensing, AI is for thinking, Blockchain is for recording, Big Data is for storing, and Cloud Computing is for hosting and processing.

To optimise food logistics and reduce food loss, the integration of IoT, AI, Blockchain, and Cloud Computing offers a comprehensive digital solution. Each technology contributes uniquely to improving supply chain efficiency (Table 1).

Table 1 Key digital technologies for food loss reduction in agroindustry

Technology	Role in Food Logistics	Key Benefits	Challenges	References
IoT (Internet of Things)	Real-time monitoring and controlling of environmental conditions (through sensors, controllers, and actuators)	Prevents spoilage, improves tracking, enhances cold chain integrity	High implementation costs, connectivity issues in remote areas	[43-45]
AI & Machine Learning	Predictive analytics for food deterioration, supply-demand forecasting	Reduces waste, optimises transportation, enhances decision-making	Requires large datasets, complex integration	[12-13,46]
Blockchain	Secure, tamper-proof traceability of the food supply chain	Increases transparency, reduces fraud, ensures food safety	Scalability, regulatory barriers	[47-50]
Cloud Computing	Centralised data management, provides scalable storage, and supports real-time data processing and decision-making.	Enables cross-stakeholder collaboration, enhances analytics	Data security, dependence on stable internet infrastructure	[16,34,50]

ML methods and algorithms are established and can be selected to suit the available data. For instance, K-Means Clustering, an unsupervised method of ML, can efficiently handle large datasets, formulate a new classification by dividing data into clusters based on similarity, accurately categorise quality levels of food based on multiple parameters, and provide precise, interpretable results[51-53]. Advanced clustering methods classify fruits into distinct maturity levels, helping stakeholders prioritise shipments and reduce spoilage[54]. An advanced supervised method, Deep Learning, achieved over 95% accuracy in predicting the ripening stages of fruits, thus enabling better logistics planning[55-56].

Beyond quality prediction, ML models are employed to detect food contamination and adulteration. By analyzing sensor data, these models can identify anomalies indicative of contamination, allowing for swift intervention to prevent compromised products from reaching consumers. This application is crucial for upholding stringent food safety standards and protecting public health. Overall, the integration of ML in food quality prediction enhances the ability to manage perishable goods effectively, resulting in reduced waste, improved product quality, and more efficient supply chain operations[41,57-58].

The synergy between IoT and ML, complemented by Cloud computing, which provides scalable storage and computational power, also extends to demand forecasting and inventory management. AI algorithms analyze data from IoT devices alongside historical sales data to predict future demand patterns accurately. This foresight allows businesses to adjust their inventory levels accordingly, reducing the risk of overstocking or stockouts and thereby optimizing resource utilization[57,59].

Blockchain technology is becoming more widely acknowledged as a key element in modernizing food logistics with its ability to improve data management, security, and traceability throughout supply chains. Blockchain records can verify that cold chain integrity was maintained throughout transportation[47-48]. Additionally, cloud platforms support collaborative efforts among various stakeholders by providing centralized access to data and applications, thereby enhancing coordination and efficiency within the supply chain[49-50].

Despite the integration of IoT, AI, Blockchain, and Cloud Computing holds immense potential to revolutionize food logistics, several barriers hinder their widespread adoption. The high costs associated with deploying IoT sensors and cloud storage present formidable financial hurdles, particularly for small-scale farmers and logistics providers[16]. Additionally, connectivity limitations in Indonesia's remote regions can disrupt real-time data transmission, reducing the effectiveness of smart monitoring systems[22]. Regulatory frameworks for blockchain-based traceability remain underdeveloped, creating uncertainty in legal compliance and cross-border food trade[60]. Furthermore, AI and predictive analytics require extensive historical data, which many agroindustry stakeholders lack due to fragmented record-keeping practices[61]. Addressing these challenges requires a coordinated effort between government bodies, private sector stakeholders, and technology providers to establish supportive policies, improve digital infrastructure, and promote industry-wide adoption of these innovations[62].

2 PROPOSED FRAMEWORK FOR SMART AGROINDUSTRY

The advent of Food Logistics 4.0 signifies a transformative shift in managing food supply chains, emphasizing the integration of advanced technologies to enhance efficiency, transparency, and sustainability. The proposed framework leverages the synergistic capabilities of the emerging advanced digital technologies.

2.1 Smart Agroindustry Design and Development

Designing a robust Smart Agroindustry Framework requires a structured approach that integrates multiple technological advancements to enhance efficiency, traceability, and sustainability. Given the complexity of modern agroindustry systems, a mind map serves as a vital tool for visualizing key components. By organizing core elements such as IoT, AI, Blockchain, and Cloud Computing, the mind map helps in defining roles, identifying works, and ensuring a cohesive implementation strategy. This structured representation facilitates the designing of a future-ready agroindustry ecosystem (Figure 1).

The design and development of smart agroindustry involve the seamless integration of digital technologies into agricultural practices and food logistics[63]. This integration aims to create a responsive and adaptive supply chain capable of real-time monitoring and decision-making. The Internet of Things (IoT), Artificial Intelligence (AI), Blockchain, and Cloud Computing in the design address the multifaceted challenges inherent in agroindustry and food logistics. The system integration framework visualises the workflows of the technology stack (Figure 2).

Food supply chain traceability and transparency have been demonstrated to be greatly enhanced by the combination of blockchain technology and Internet of Things devices. IoT devices gather data on a number of parameters in real time. In order to create an unchangeable ledger that stakeholders can access to confirm the legitimacy and state of food products, this data is subsequently stored on a blockchain. A study by Moudoud et al.[64] proposes an IoT-blockchain architecture utilising oracles and smart contracts to enhance data reliability and automate processes within the supply chain.

Artificial Intelligence can further augment blockchain applications by managing and pruning blockchain data to optimise performance. It has been suggested that supply chain performance can be improved through the use of BDI (Beliefs, Desires, and Intentions) agents in an AI-enabled blockchain solution. These agents effectively handle blockchain data, guaranteeing that the system is responsive to the ever-changing demands of food logistics and remains scalable[48].

The IoT-AI integration plays a crucial role in optimising food logistics by enabling real-time data processing and intelligent decision-making. IoT devices continuously gather data, ensuring the safety and quality of food products. AI processes this vast amount of data, identifying patterns, predicting potential risks, and optimising logistics operations. AI-driven analytics enhance decision-making by providing insights into supply chain efficiencies, reducing food loss, and improving transportation routes[65].

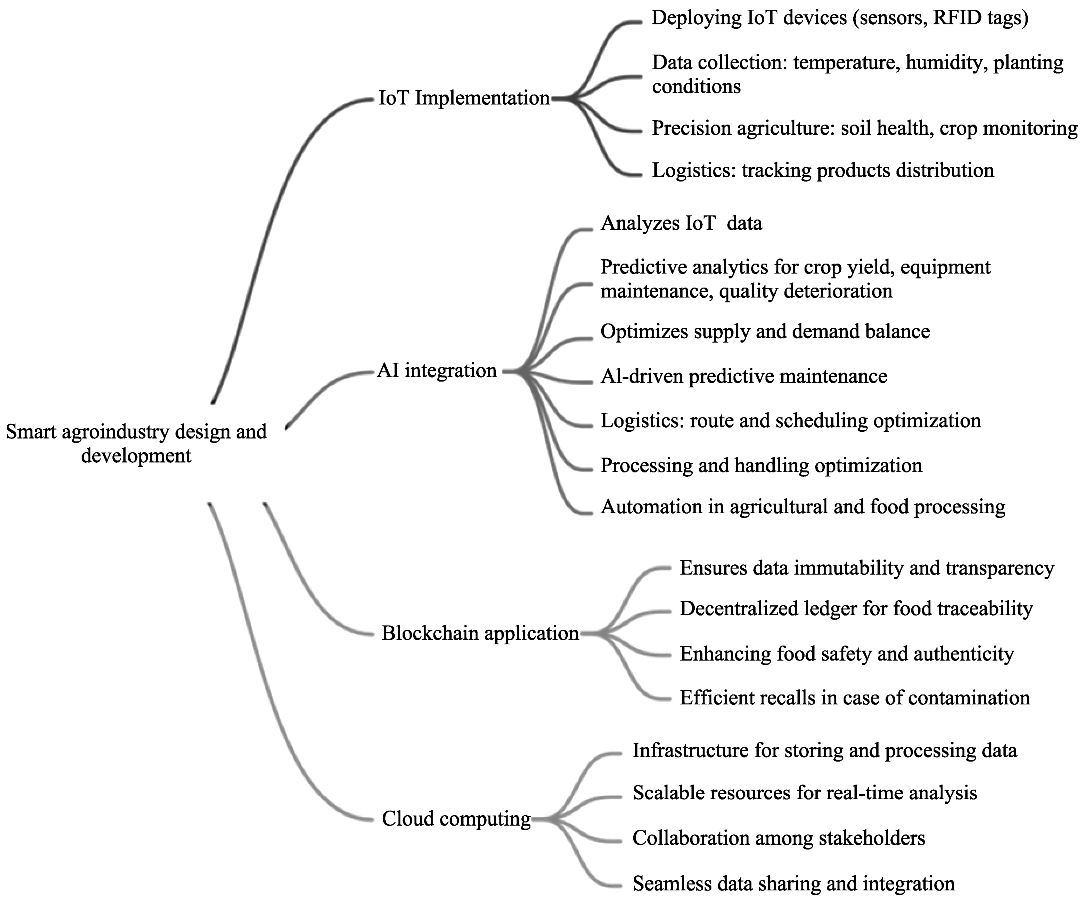

Fig.1 The mindmap of smart agroindustry design and development

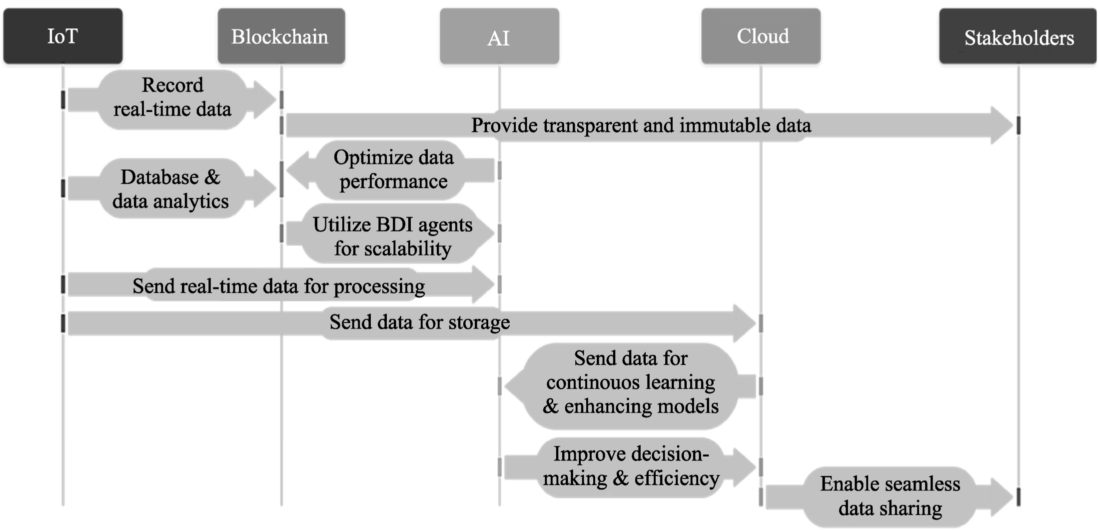

Fig.2 System integration framework

The integration of these technologies fosters a smart agroindustry that is efficient, transparent, and resilient, capable of adapting to dynamic market demands and environmental conditions. However, while the integration of these technologies offers numerous benefits, challenges such as data interoperability, security concerns, and the need for standardization persist. Ensuring that different systems and devices can communicate effectively requires the development of universal standards and protocols[21]. Additionally, safeguarding data integrity and privacy is crucial, especially when dealing with sensitive information related to food safety and quality[66-67]. Addressing these challenges necessitates collaborative efforts among stakeholders, including technology developers, food industry players, and regulatory bodies[62].

2.2 Application Roadmap

The proposed Smart Agroindustry framework follows a structured three-stage roadmap: short-term, medium-term, and long-term implementation. Each stage progressively builds upon technological integration, infrastructure expansion, and policy support to ensure sustainable and scalable adoption of IoT, AI, blockchain, and cloud computing in the food supply chain (Figure 3). The timeline spans 5 years of development, from pilot projects to nationwide implementation (Table 2).

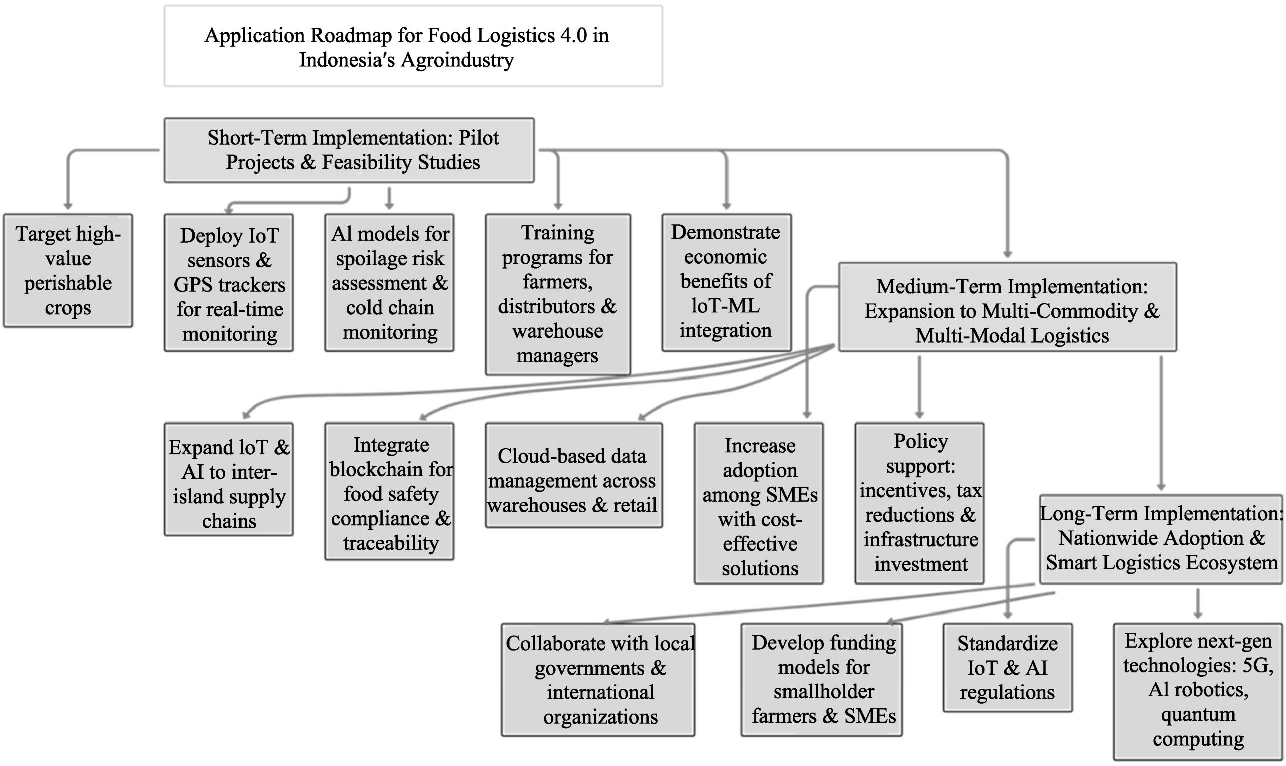

Fig.3 Roadmap for technology stack implementation in smart agroindustry

1. Short-term implementation: pilot projects and feasibility studies

The first phase of the roadmap focuses on small-scale pilot projects targeting high-value perishable crops such as chilli and mango, beef, seafood, and dairy products. These commodities are selected due to their economic significance and vulnerability to spoilage during transportation. IoT devices, such as temperature and humidity sensors and GPS trackers, are installed in storage facilities and vehicles to collect real-time environmental data. This data is then processed using machine learning models, which predict ripeness, monitor cold chain integrity, and assess potential spoilage risks[13].

To ensure a smooth transition to digitalised logistics, training programs are essential for supply chain actors, including farmers, distributors, and warehouse managers. These training programs focus on operating IoT devices, interpreting AI-driven predictions, and implementing blockchain-based traceability systems. The primary goal of this phase is to demonstrate the feasibility and economic benefits of technology integration in the supply chain before scaling implementation on a larger scale.

2. Medium-term implementation: expansion to multi-commodity and multi-modal logistics

Once pilot projects have proven successful, the framework will be expanded to additional agricultural sectors beyond high-value crops. This phase involves integrating IoT and AI-driven logistics networks into inter-island supply chains, ensuring robust real-time monitoring for remote regions with limited infrastructure. The medium-term goal is to increase adoption rates among small and medium enterprises (SMEs) by developing cost-effective, scalable digital technology solutions that cater to their specific needs. Policy interventions, including government incentives, tax reductions, and digital infrastructure investments, will play a crucial role in ensuring widespread accessibility to these technologies.

Table 2 Three-phase roadmap and implementation timeline for smart agroindustry in Indonesia.

Technology / Action	Key Actions	Expected Outcomes	Phase 1 (Years 1–2)	Phase 2 (Years 2–4)	Phase 3 (Years 4–5)	Challenges & Solutions
IoT Implementation	Deploy IoT sensors in high-risk perishable commodities (vegetables & fruits, meat & seafood, dairy)	Improved cold chain monitoring, reduced spoilage	Pilot deployment in key regions	Expansion to multi-commodity supply chains	Nationwide adoption in agroindustry logistics	**Challenges:** High costs, connectivity issues **Solutions:** Public-Private Partnership, government incentives, infrastructure upgrades
AI & Predictive Analytics	AI models for spoilage risk and demand forecasting	Optimised inventory, waste reduction	AI for spoilage risk assessment	AI-driven demand forecasting	AI-powered automation & robotics	**Challenges:** Requires large datasets; training needed **Solutions:** Data-sharing frameworks, AI training programs
Blockchain for Traceability	Secure food tracking & safety compliance	Enhanced transparency, reduced fraud	—	Limited-scale integration for traceability	Nationwide blockchain traceability	**Challenges:** Scalability, regulatory uncertainty **Solutions:** Policy development, industry collaboration
Cloud Computing Integration	Real-time data sharing & analytics	Faster decision-making, improved coordination	—	Cloud-based supply chain platform	Full-scale national cloud infrastructure	**Challenges:** Data security, dependence on stable internet **Solutions:** Cybersecurity policies, public-private investments
Training & Capacity Building	Digital literacy & technology adoption for stakeholders	Improved adoption & efficiency	Training for farmers & logistics providers	Expansion to SMEs & inter-island logistics	Nationwide digital literacy programs	**Challenges:** Resistance to change, skills gap **Solutions:** Incentives, nationwide training initiatives
Policy & Regulatory Frameworks	Digital governance for smart agroindustry	Standardised legal framework for smart food logistics	—	Drafting regulations for traceability	Full legal standardisation for Food Logistics 4.0	**Challenges:** Slow policy adoption, enforcement issues **Solutions:** Multi-stakeholder collaboration, regulatory reforms

3. Long-term implementation: nationwide adoption and smart logistics ecosystem

The final phase focuses on nationwide adoption, transforming Indonesia's food supply chain into a fully integrated and intelligent supply chain ecosystem. This stage involves collaborating with local governments, industry stakeholders, and international organisations to establish standardised IoT and AI regulations.

To support nationwide digital transformation, funding models will be developed to subsidise the adoption costs for smallholder farmers and SMEs, ensuring that technological advancements are inclusive and equitable. Additionally, next-generation innovations such as 5G-enabled IoT devices, AI-powered robotic automation, and quantum computing-based logistics optimisation will be explored to further enhance supply chain resilience.

3 CONCLUSION AND RECOMMENDATIONS

Indonesia's agroindustry faces persistent food loss and waste (FLW) due to inefficient logistics, inadequate infrastructure, and a lack of real-time data integration. This study proposes a Smart Agroindustry Framework that integrates IoT, AI, Blockchain, and Cloud Computing to enhance food supply chain efficiency. A structured three-phase, 5-year roadmap ensures a gradual transition from pilot implementation to nationwide adoption, addressing key challenges such as infrastructure limitations, policy gaps, and stakeholder readiness.

By leveraging these technologies, Indonesia can reduce economic losses, enhance food security, and minimize environmental impact while also serving as a model for other developing nations.

To ensure successful implementation, Indonesia must prioritize expanding its digital infrastructure, strengthening policy support, and fostering multi-stakeholder collaboration. Early investment in cold chain logistics, blockchain-based traceability, and AI-driven analytics is crucial for optimizing food distribution. Additionally, capacity-building programs for farmers and supply chain managers will facilitate adoption and ensure long-term sustainability. By committing to a coordinated, technology-driven approach, Indonesia can establish a resilient, data-driven agroindustry, reducing food waste while promoting economic and environmental sustainability.

REFERENCES

See in Chinese version P47-58.