African Journal of Advanced Pure and Applied Sciences (AJAPAS)
Online ISSN: 2957-644X
Volume 4, Issue 4, 2025
Page No: 60-69
Website: https://aaasjournals.com/index.php/ajapas/index

ISI 2025: 1.126	SJIFactor 2024: 6.752	معامل التأثير العربي: 1.62

Health Risks and Economic Opportunities of Practices Reusing Wastewater in Agriculture: An Overview

Adel S. Faskol *
Libyan Authority for Scientific Research, Benghazi Branch, Libya

المخاطر الصحية والفرص الاقتصادية لممارسات إعادة استخدام مياه الصرف الصحي في الزراعة: نظرة عامة

عادل صالح فصكول [1*]
الهيئة الليبية للبحث العلمي، فرع بنغازي، ليبيا

*Corresponding author: adel.s.faskol@gmail.com

Received: August 10, 2025	Accepted: September 26, 2025	Published: October 07, 2025

Abstract:
The practice of reusing wastewater in agriculture is widespread all over the world. However, there are also raised concerns regarding these practices that may cause negative impacts on human health and the environment. The overall objective of this literature review is to synthesize current evidence and possible future knowledge on health risks and economic opportunities associated with wastewater reuse practices in agriculture, the basic design of this study focusing on a literature review of the 10 open-access studies published in the ScienceDirect database over the past five years, from 2020 to 2025. And it highlights two subjects: "Health Risks", which is the scope of the excreted pathogens (bacteria, viruses, and parasites) and their contamination pathways into the food chain via irrigated crops. And "Economic Opportunities", which is the scope of nutrient provisioning that enhances crop yield. The results of this literature review conclude that practices reusing untreated or partially treated wastewater in agriculture cause increased loads of pathogens. While advanced treatment can produce safe treated wastewater in agriculture. However, the high economic cost of advanced treatment often renders them impractical in low-income countries. To satisfy health targets beside those related to excreta diseases, there must be an integration of realistic treatment levels, stringent regulatory frameworks, farmer education, and targeted crop selection. All these procedures are considered very important to maximize the economic opportunities of reusing wastewater in agriculture and human health safety and environmental protection.

Keywords: Wastewater reuse practices, Excreted pathogens, Wastewater-irrigated food crops.

الملخص
تنتشر ممارسة إعادة استخدام مياه الصرف الصحي في الزراعة على نطاق واسع في جميع أنحاء العالم ومع ذلك، تثار مخاوف بشأن هذه الممارسات التي قد تسبب آثارًا سلبية على صحة الإنسان والبيئة. الهدف العام من هذه المراجعة الأدبية هو تجميع الأدلة الحالية والمعارف المستقبلية المحتملة حول المخاطر الصحية والفرص الاقتصادية المرتبطة بممارسات إعادة استخدام مياه الصرف الصحي في الزراعة، حيث يركز التصميم الأساسي لهذه الدراسة على مراجعة أدبية لعدد 10 دراسات مفتوحة المصدر نشرت في قاعدة بيانات (ScienceDirect)، على مدى السنوات الخمس الماضية، منذ عام 2020 م إلى عام 2025 م. وتسلط هذه الدراسة الضوء على موضوعين أساسيين هما: "المخاطر الصحية" وهو نطاق مسببات الأمراض الغائطية (البكتيريا ، الفيروسات ، الطفيليات)، ومسارات تلويثها في السلسلة الغذائية عبر المحاصيل المروية بمياه الصرف الصحي. "الفرص الاقتصادية" وهو نطاق توفير العناصر الغذائية التي تعزز إنتاجية المحاصيل الزراعية. أظهرت نتائج هذه المراجعة الأدبية إلى أن ممارسات إعادة استخدام مياه الصرف الصحي غير المعالجة أو المعالجة جزئيًا في الزراعة تسبب زيادة في أحمال مسببات الأمراض الغائطية. وبينما يمكن للمعالجة المتقدمة لمياه الصرف الصحي إنتاج مياه آمنة يمكن استخدامها في الزراعة، إلا أن التكلفة الاقتصادية المرتفعة للمعالجة المتقدمة لمياه الصرف الصحي غالبًا ما تجعلها غير عملية في البلدان منخفضة الدخل. ولتحقيق الأهداف الصحية المرتبطة بالأمراض الغائطية، لا بد من اتباع طرق متعددة

تضمن مستويات معالجة واقعية لمياه الصرف الصحي، ووضع مواصفات فنية صارمة، وتوعية المزارعين، واختيار المحاصيل المستهدفة. تعتبر جميع هذه الاجراءات بالغة الأهمية لزيادة الفرص الاقتصادية لممارسات إعادة استخدام مياه الصرف الصحي المعالجة في الزراعة، وسلامة صحة الانسان وحماية البيئية.

الكلمات المفتاحية: ممارسات إعادة استخدام مياه الصرف الصحي، مسببات الأمراض الغائطية، المحاصيل الزراعية المروية بمياه الصرف الصحي.

1. Introduction

According to the Food and Agriculture Organization of the United Nations (FAO), water availability is inextricably related to food availability, both of which are threatened by the effects of global warming [1]. Practices reusing wastewater in agriculture may offer a variety of advantages, such as plants using nutrients in wastewater, resulting in boosted food security and crop yields [2]. Could manure roughly 6 to 7 tonnes of wheat with the nutrients found in the wastewater produced by 30 people. (In Europe, 4.5 kg nitrogen + 0.5 to 1.5 kg phosphate + 0.5 to 1.7 kg potassium per person each year), which would provide food for twice as many people [3]. On the other hand, practices reusing untreated or partially treated wastewater in agriculture can be the origin of waterborne infections caused by parasitic protozoa and free-living amoebae (FLA), including Blastocystis, Acanthamoeba, Cyclospora, Toxoplasma, Cryptosporidium, and Vermamoeba [4]. Among the microorganisms found in wastewater are Staphylococcus, Corynebacterium, Propionibacterium spp., and Pseudomonas aeruginosa. Salmonella enterica, Shigella spp., and Staphylococcus aureus are pathogens of concern with regard to reusing wastewater [5]. The runoff, sewer leakage, and effluents of the wastewater treatment plant are the main ways that large quantities of pathogens might enter aquifers. Treated municipal wastewaters still release pathogens into the environment despite treatment efforts [6]. The surface water streams are important sources of agricultural irrigation. Farmers and consumers are so frequently exposed to pathogen contamination, particularly in developing nations. Several risk assessments were conducted in order to reduce the health concerns associated with the growing number of unplanned and indirect wastewater irrigations. Risk mitigation frameworks like the Stockholm framework, sanitation safety planning, the multiple-barrier method, sanitary inspection, risk matrix, and Quantitative Microbial Risk Assessment (QMRA) have been developed and implemented [7]. Traditional wastewater treatment techniques have drawbacks, such as high expense and high energy usage. Using inexpensive, environmentally friendly, and safe methods like biological elimination, remediation, or decolorization with different kinds of microorganisms is one way to solve the problem. The most common organisms used in biological wastewater treatment facilities to remove organic contaminants are bacterial strains. While fungal strains can produce a number of degradative enzymes and surface proteins that are crucial for the biodegradation or biosorption of pollutants present in wastewater, filamentous fungi have received far less attention than bacteria for the purpose of wastewater treatment [8]. The World Health Organization (WHO) issued guidelines for the safe handling and repurposing of wastewater, excreta, and greywater [2]. In Bogotá, Colombia, for instance, the water used for agricultural irrigation comes from the Bogotá River, despite pollution levels ranging from acceptable to moderate. In the upper and middle basins of the Bogota River, 97% of the water is used to irrigate crops like strawberries, vegetables, potatoes, and grass [9]. Recycling of wastewater can increase economic efficiency and bring in additional revenue. The recycling could actively improve the environment while also lowering financial and environmental expenses. In exchange for the resources and services that nature offers, societies can use the recovered resources to supply the natural environment with reciprocal services. A symbiotic link between humanity and the natural environment can be fostered by evaluating the possible benefits of nature. Additionally, this can lead to a more comprehensive perspective on wastewater treatment, which can lead to more opportunities for resource recovery [10].

2. Material and methods

This is a literature review of scientific articles titled "Health risks and economic opportunities of practices reusing wastewater in agriculture". The data was collected from ScienceDirect, chosen for its extensive collection of high-quality journals related to environmental science, engineering, and public health. The search was limited to articles published between 2020 and 2025, where the data was collected on 23 July 2025, using search queries based on keywords: (“wastewater reuse practices”) AND (“excreted pathogens”) AND (“wastewater-irrigated food crops”). The search yielded 43 research articles relevant to the keywords. The titles and abstracts of the articles were assessed and screened for relevance to this overview. Out of these publications, this screening process resulted in the final selection of 10 open access-type articles relevant to the objective of this article, which formed the core bibliography base for this overview. The data from each of the 10 articles were extracted into a standardized matrix. The extracted information included author(s) and publication year, study location, type of wastewater and treatment level, pathogens investigated, crops studied, key findings related to pathogen persistence and contamination, economic parameters assessed such as cost savings, yield increase, and investment cost, and main conclusions regarding risk-benefit balance. A narrative synthesis approach was employed to integrate findings across studies.

3. Results and discussion

3.1. Health risks of reusing wastewater in agriculture:

Reuse of untreated or partially treated wastewater causes a health risk associated with agricultural reuse, as it contains excreted pathogens. The magnitude of the risk depends on the type of the pathogen strains and their concentration in water irrigation or the rate of contamination of the crop with excreted pathogens. On the other hand, reusing wastewater in agriculture provides advantages such as the nutrients which the crops need throughout the year. Table 1 shows the summary of key health risks via irrigated crops with wastewater from reviewed studies. Figure 1 shows transmission of bacteria, viruses, and parasites from crops irrigated with wastewater to humans.

Table 1 Summary of key health risks via irrigated crops with wastewater from reviewed studies

Collected samples	Type of excreted pathogens	Route of exposure	Country	Reference
Raw faecal sludge/Dried faecal sludge	E. coli Enterococcus spp Viable Ascaris eggs	Found in vegetable samples, and leafy vegetables (onion leaves and amaranth)	Uganda	[2]
Irrigation water/ Soil/Organic vegetable	Proteobacteria Firmicutes Actinobacteriota Bacteroidota Acidobacteriota	Soil samples exhibited the highest microbial richness, followed by water used for irrigation and organic vegetables	Spain	[4]
Untreated greywater/ Treated greywater	Rotavirus	The discharge of untreated greywater onto soil surfaces poses a risk for children and adults	Brazil	[5]
Groundwater	Human adenovirus (HAdV) Enterovirus (EV) Norovirus (NoV) Adenoviridae Astroviridae Caliciviridae Enterovirus Herpesviridae Papillomaviridae Picornaviridae Polyomaviridae Reoviridae Adenoviridae Astroviridae Circoviridae Herpesviridae families Baculoviridae Dicistroviridae Iflaviridae Iridoviridae Nodaviridae families	Diversity of waterborne viruses in groundwater, particularly focusing on the Besòs River Delta aquifer in Catalonia	Spain	[6]
Surface water	Faecal coli E. coli Enterococcus	Health Risks for Farmers	Bangladesh	[7]

Collected samples	Type of excreted pathogens	Route of exposure	Country	Reference
Lettuce Strawberries	E. coli Enterococcus Clostridium sp Salmonella spp CB390 Phages F-specific RNA Phages Bacteroides Markers (CF128 and HF183) Bifidobacterium Markers (ADO and DEN) Helicobacter pylori (H. pylori)	Potential risks to food safety	Colombia	[9]

Bacterial infections: The raw faecal sludge had significant concentrations of E. coli (mean 5.6 $\log_{10}$ cfu g^{-1}), while dried sludge displayed a wide range of variability, ranging from below detection limit to 6.4 $\log_{10}$ cfu g^{-1}. Enterococcus spp. was frequently found in all dried faecal sludge samples, with an average concentration of 4.9 $\log_{10}$ cfu g^{-1}. The large concentrations of E. coli and Enterococcus were found in soil samples of the fields fertilized with chicken manure [2]. Where the beta diversity analysis indicated significant differences between soil and water and between soil and fresh produce. However, a clustering pattern between water and fresh produce suggested potential microbiological transfer. Eleven genera were common to all analyzed samples, including potentially pathogenic genera like Pseudomonas and Enterobacter. Pseudomonas was highly abundant in water and food crops, and Aeromonas was also identified [4]. The seasonal variation was significant, with the highest concentrations of TC, FC, and E. coli occurring during the summer and monsoon seasons. This is attributed to factors like higher atmospheric temperatures favouring bacterial growth and increased runoff during monsoons from built-up areas, septic tanks, and wet markets. While Enterococcus concentrations were lower in summer than in monsoon, possibly due to light accelerating its decay. The spatial variation was significant spatial variation in TC, FC, and E. coli concentrations across different sources. Thus, canals and drains showed higher contamination than rivers, likely due to direct discharge from households and industries, while river water benefits from dilution and tidal effects. Moreover, the primary exposure route identified was the oral route through accidental ingestion of contaminated water while working in the field. Farmers often work barefoot, increasing contact with polluted surface water [7]. The microbiological indicator presence in food crops, where all analyzed strawberry and lettuce samples, regardless of their origin (fields, marketplaces, or supermarkets), tested positive for total coliforms. The concentrations observed were high, ranging from 5.3 to 6.5 (Log_{10}CFU/g). Also, Escherichia coli (E. coli) was detected in one strawberry sample from fields and one from marketplaces, as well as one lettuce sample from a marketplace, with a prevalence of 12.5% in both strawberry cases. The maximum concentrations were 5.7 and 5.30 (Log_{10}CFU/g) for strawberries and 6.0 (Log_{10}CFU/g) for lettuce. Notably, E. coli was not found in samples from supermarkets. The Enterococcus was frequently found, particularly in supermarket strawberries (44.4%) and field strawberries (37.5%). In lettuce, Enterococcus was more common in field and marketplace samples (62.5%) than in supermarket samples (44.4%). Clostridium sp. (Sulfate-Reducing): both vegetative and spore forms of Clostridium sp. were widely present, ranging from 37.5% to 88.9% in strawberries and 25% to 100% in lettuce, indicating its widespread environmental distribution. The difference in mean concentrations between the vegetative and spore forms did not exceed 0.4 ($\log_{10}$CFU/g). Salmonella spp. was detected more frequently in lettuce samples (77.7%-87.5%) compared to strawberry samples (12.5%-62.5% [9].

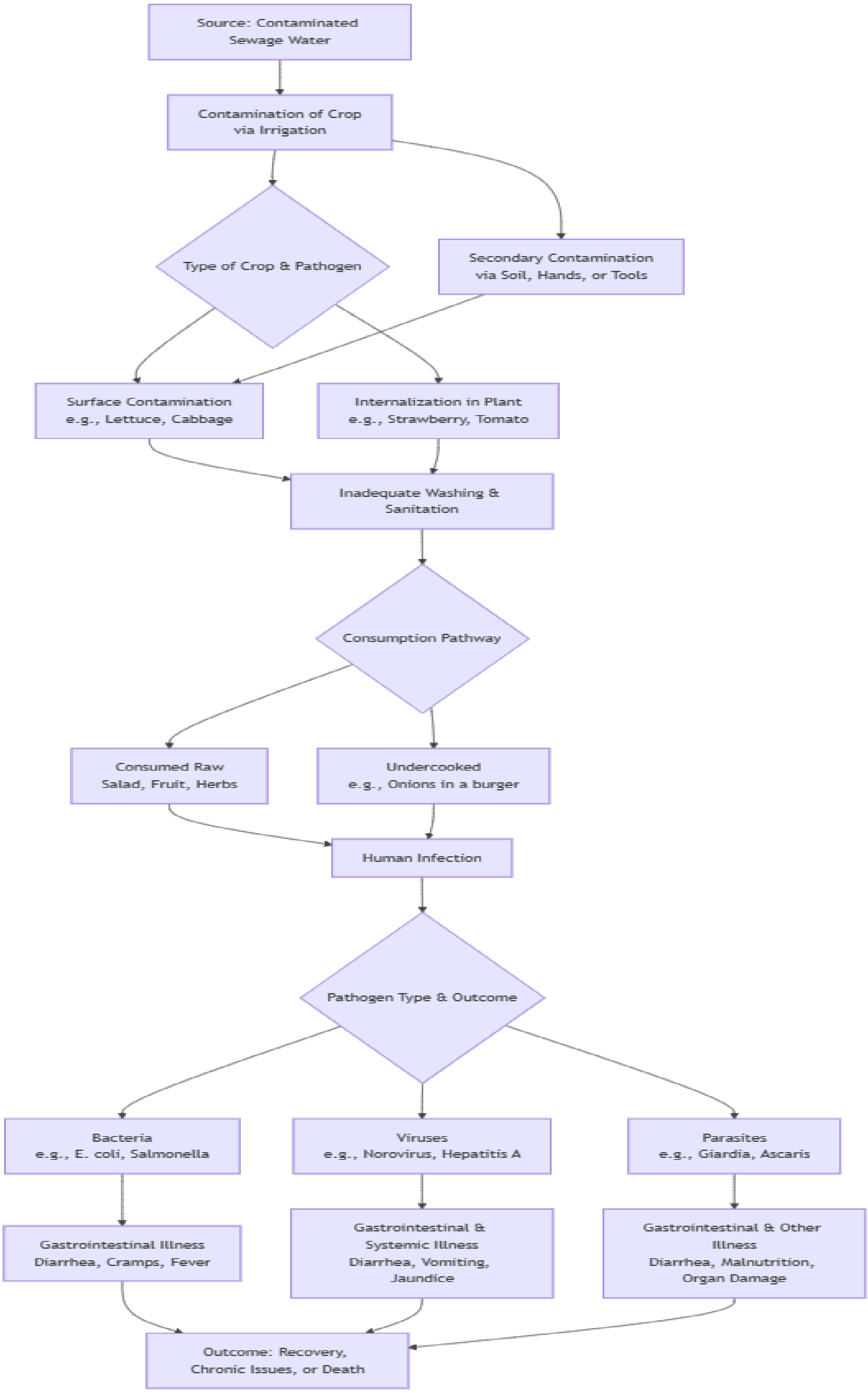

Figure 1: Transmission of bacteria, viruses, and parasites from crops irrigated with wastewater to humans.

Parasitic infections: Vegetable samples were found to be contaminated with Ascaris, with cabbages having an average of 172 viable eggs per item (0.4 egg g^{-1}, 67% viability) and leafy vegetables (onion leaves and amaranth) having an average of 17 eggs g^{-1} (65% viability). Viable Ascaris eggs were detected in all samples, with the highest concentration in raw sludge (mean 66 eggs g^{-1}, 52% egg viability). Mean Ascaris concentration was lower in dried sludge (21 eggs g^{-1}, 53% viability) and sludge-fertilized soil (15 eggs g^{-1}, 63% viability). Leafy vegetables posed a several-fold higher risk than cabbage due to higher Ascaris egg concentration [2]. The soil samples showed the highest number of observed eukaryotic features, followed by water and fresh produce. Significant differences in Faith's Phylogenetic Diversity were found across all sample types. Where eukaryotic phyla distribution varied by sample type. In water, Chlorophyta (30.95%) and Diatomea (22.59%) were predominant. Soil was dominated by Phragmoplastophyta (63.58%), while fresh produce primarily contained Basidiomycota (42.18%) and Phragmoplastophyta (29.48%). The eukaryotic core microbiome genera are Magnoliophyta, Sorodiplophrys, and Trebouxiophyceae. Cryptosporidium, a common etiological agent of waterborne outbreaks and a cause of diarrhoea, was detected in all sample types, with the highest relative abundance in fresh produce [4].

Viral infections: Garden irrigation with wastewater presented a medium risk for children (60), with rotavirus being the main pathogen responsible. However, the greywater irrigation may not be a significant source of disease, especially in colder months [5]. The presence of HAdV in over half of the groundwater samples under analysis means peoples faecal pollution. Mean HAdV concentrations varied from 1.23E+02 to 3.66E+03 GC, genome copies per membrane. On occasion, genogroups I and II of Enterovirus (EV) and Norovirus (NoV) were found. At both sampling depths (3 and 11 meter), EV was reliably detected. No Correlation with Precipitation, where there was no discernible relationship between the frequencies of virus detection and the total amount of precipitation. The aquifers varied virome was discovered via targeted enrichment sequencing (TES), which identified 21 distinct viral families. Twelve of these species are known to infect humans. Significant human pathogens detected included Adenoviridae, Astroviridae, Caliciviridae, Enterovirus, Herpesviridae, Papillomaviridae, Picornaviridae, Polyomaviridae, and Reoviridae. A wide diversity of avian, bovine, cervid, equid, porcine, and rabbit viruses (e.g., from Adenoviridae, Astroviridae, Circoviridae, and Herpesviridae families) were found. Additionally, many insect-infecting viruses (e.g., from Baculoviridae, Dicistroviridae, Iflaviridae, Iridoviridae, and Nodaviridae families) were detected, some of which are used as bio-insecticides [6]. The existence of viral indicators (CB390 phages), These phages were identified in strawberries from the marketplaces (62.5%), supermarkets (55.5%), and fields (50%). In lettuce, CB390 phages were found in marketplace samples (25%) and supermarket samples (44.4%), but not in field samples. The F-specific RNA phages' detection was lower for these phages in strawberries, with presence in supermarket samples (33.3%), field samples (25%), and market samples (12.5%). In lettuce, they were found in marketplace samples (12.5%), certainly not in field or store samples [9]. The overall, the findings underscore the complex interplay of microbial communities with negative effects on food crops, highlighting the potential for microbiological transfer from polluted water to food crops. This emphasizes the critical need for robust microbiological control and comprehensive management strategies to ensure food safety [4].

3.2. Economic opportunities of reusing wastewater in agriculture:

Despite the evident health risks, the reviewed literature confirms the significant economic advantages that drive the adoption of wastewater irrigation, particularly in water-scarce regions. Benefits of reclaimed wastewater where is an important supplier of plant nutrients, including nitrogen (N), phosphorus (P), and potassium (K), which can maintain soil fertility and productivity. It can greatly lessen the requirement for conventional fertilizers and water, potentially saving up to 25% on fertilizer consumption. Farmers can reduce costs associated with purchasing chemical fertilizers. The use of treated wastewater can lead to higher crop yields and improved plant growth, as observed in studies on tomatoes, olive trees, and mung beans. The direct introduction of nutrients to the root zone via fertigation minimizes nutrient losses to deeper soil layers or groundwater. It helps reduce the discharge of nutrients into surface waters, thereby mitigating environmental pollution and eutrophication risks [1]. Nutrient recovery provides possible economic opportunities and reduces the demand for precious public land and operational expenditures. The approach is particularly attractive for rural areas or new buildings where centralized systems are absent or costly to upgrade. Industrial wastewaters, especially from food processing, also offer high concentrations of biodegradable organic matter and nutrients, presenting an opportunity for businesses to benefit from recovered fertilizers and reclaimed water. Recovered nutrients are often perceived negatively due to their origin from wastewater. Educating society and promoting the sustainable label of recovered fertilizers can help gain product acceptance and overcome the conservative nature of the fertilizer market. [3]. Nitrogen assimilation, through the recovery of ammonium sulphate and its application in agriculture, where a biomass nitrogen assimilation of $2.57 \pm 0.04 \times 10^5$ kg/y was achieved. The stabilization method of organic matter, such as anaerobic digestion, is crucial, with products having lower volatile solids preferred for higher sequestration. Which includes nitrogen recovery as ammonium sulphate, organic matter as cellulose fibres and sludge digestate, and phosphorus recovery as struvite from incinerated sludge ash) was identified as the preferred option. It provided the same FR and nitrogen BA as other alternatives but yielded the highest phosphorus BA. Recovered waste nutrients can be transformed into fertilizers with high uptake efficiencies, contributing to more effective biomass assimilation and reducing reactive nutrient emissions. Additionally, the method helps identify pathways for restoring soil organic matter, mitigating climate change, and improving soil quality [10]. Fungi can improve the biodegradability of high starch-containing wastewater and produce valuable products like bioflocculants, pigments, and protein-rich biomass. Filamentous fungi can convert organic matter, nitrogen, and phosphorus from fish industry wastewaters into biomass favorable for energy and nutrient production. White rot fungi and their oxidoreductase enzymes are suggested as a cost-effective and environmentally friendly solution for the purification of pharmaceutical substances. Filamentous fungi exhibit significant potential in absorbing and sequestering metal contaminants from industrial wastewaters. This occurs through biosorption, where microbial biomass passively or actively traps organic and inorganic substances. Their cell walls contain functional groups like hydroxyl, amine, and carboxyl, which are useful for biosorption. Dead cells of these microorganisms are also effective biosorbents [8]. In summary, recovered nutrients from wastewater, offers a sustainable path to address the increasing demand for fertilizers and water irrigated. While significant opportunities exist, overcoming economic, societal, and regulatory barriers through strategic interventions and stakeholder engagement is essential. Figure 2 shows the economic opportunities of reusing treated wastewater in agriculture.

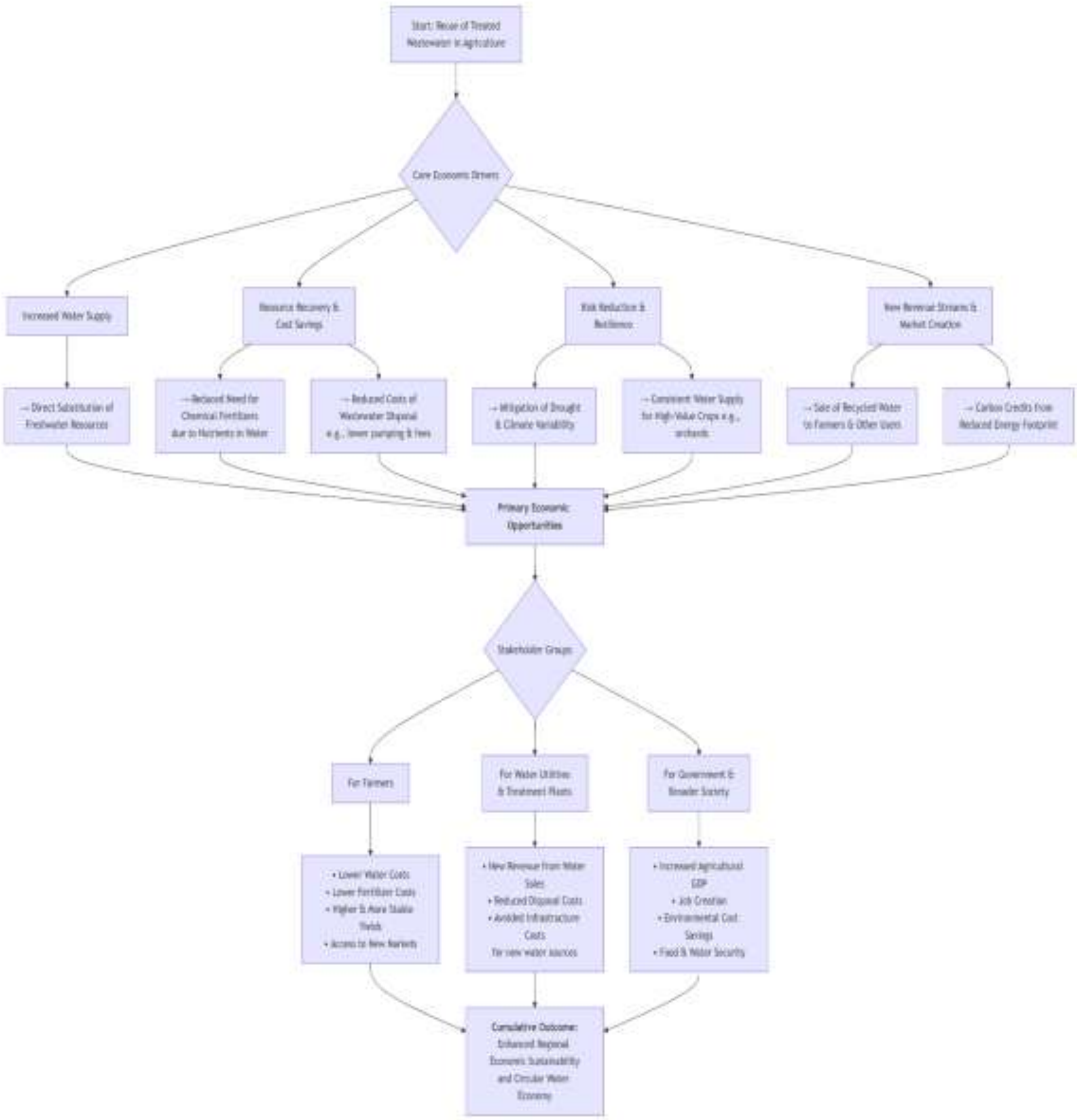

Figure 2: Economic opportunities of reusing treated wastewater in agriculture

3.3. Balancing the health risks and economic opportunities:

The synthesis of these 10 studies reveals a clear, yet complex, narrative: the economic opportunities of wastewater reuse are tangible and immediate for farmers and communities, but they are inextricably linked to significant public health risks that cannot be ignored. The central challenge is not to choose between benefit or risk but to manage the practice to maximize the opportunities and minimize the health risks. Figure 3 shows the balancing the pathogen transmission and economic opportunities in wastewater reuse.

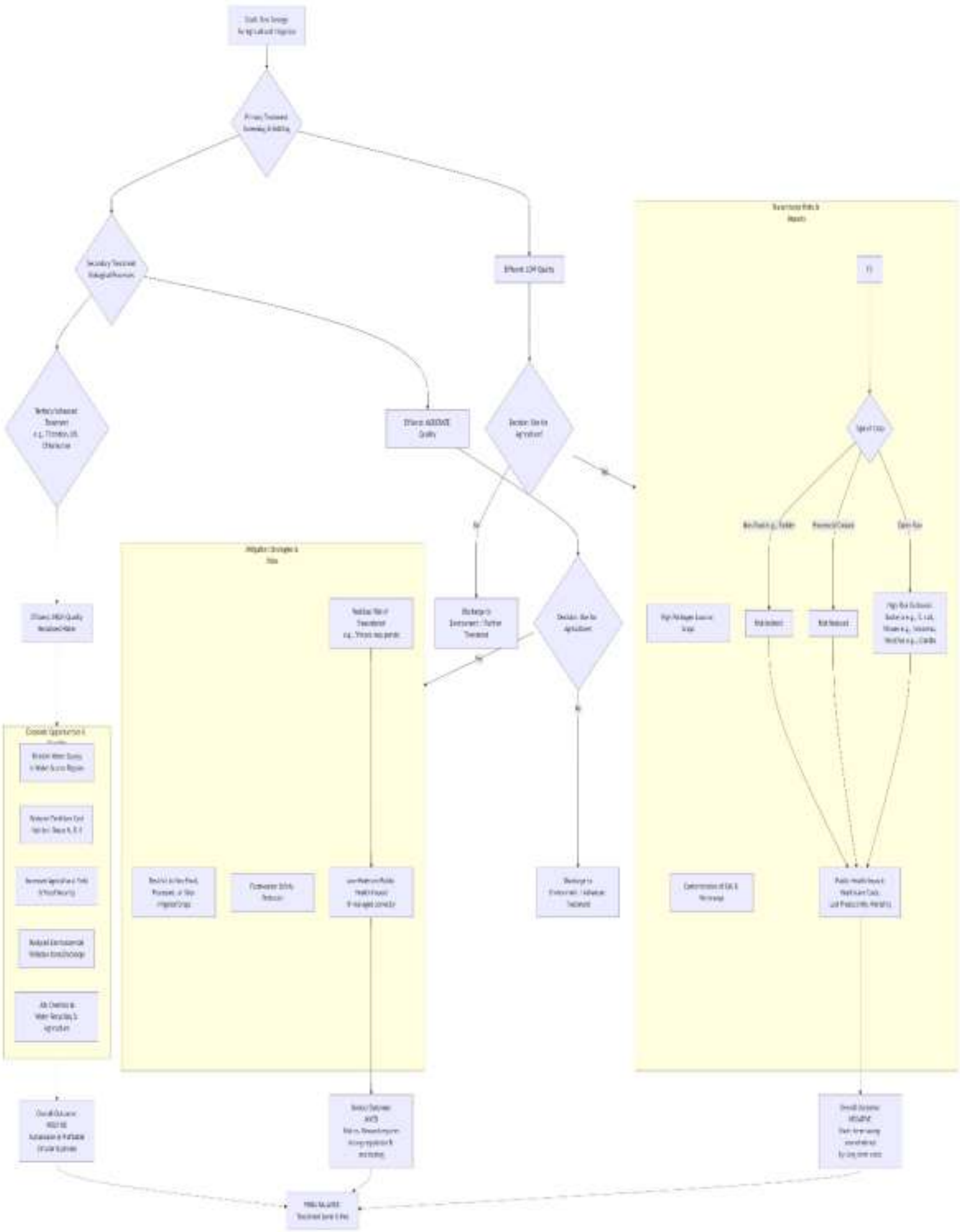

Figure 3: Balancing the pathogen transmission and economic opportunities in wastewater reuse.

The treatment divide: The most prominent theme across this literature review is the critical role of wastewater treatment level. Studies like [2], [4], [5], [6], [7], and [9] demonstrate that inadequate treatment simply transfers the pathogen load from water to crops. In contrast, the studies like [1], [3], [10], and [8] show that advanced treatment can produce safe treated wastewater in agriculture. Therefore, the economic opportunities of wastewater reuse are clear and useful for farmers and communities. However, the high capital and operational costs of these technologies create a "treatment divide", where high-income countries can safely harness the benefits, while low-income countries, where the practice is most common, are often left with high-risk, low-treatment options.

The need for context-specific solutions: A one-size-fits-all approach is impractical. The reviewed studies call for a multi-barrier approach that is tailored to local economic, technical, and social contexts. This approach can include the appropriate treatment level and investing in robust, but not necessarily the most advanced, treatment. Waste stabilization ponds, while land-intensive, can be highly effective and low-cost in suitable climates. Crop restriction, where directing lower-quality effluent to non-food crops (e.g., cotton, biofuel crops) or processed food crops (e.g., cereals, which are cooked), is a highly effective and low-cost risk reduction strategy. Post-harvest interventions, like washing, have limited efficacy, but promoting simple point-of-use interventions like vinegar or bleach soaking in households can provide a final risk reduction barrier. Farmer and consumer education where awareness of risks is low among many farmers. Education on hygiene practices, use of personal protective equipment, and safe irrigation methods is crucial.

The role of policy and regulation: Strong policy and guidelines are the backbone of safe reuse of wastewater in agriculture. As with the successful countries with clear water reuse standards. On the other hand, it underscores the problem of non-existent guidelines in low-income countries. However, effective policy and guidelines must not only set standards but also provide support mechanisms, such as subsidies for safer irrigation technologies or public-private partnerships for building treatment infrastructure.

4. Conclusion

This overview, based on a synthesis of recent literature of the 10 open-access studies published in the ScienceDirect database over the past five years, from 2020 to 2025, confirms that the reuse of wastewater in agriculture is a practice of immense potential and profound challenge. Its economic opportunities, from direct cost savings and increased yields to enhanced farmer resilience and macroeconomic gains, are undeniable and crucial for sustainable water management and food security, especially in arid regions. However, these benefits are critically contingent on the effective mitigation of associated health risks from excreted pathogens.

Future efforts must be directed towards:

1. Research and Innovation: Developing and scaling up robust, low-cost, and energy-efficient treatment technologies tailored for resource-limited settings. Research into natural treatment systems and bio-based filtration media should be prioritized.
2. Integrated Risk Management: Promoting and validating the efficacy of multi-barrier approaches that combine partial treatment with agronomic management (crop selection, irrigation method) and post-harvest handling practices.
3. Capacity Building and Policy: Strengthening institutional frameworks for monitoring, regulation, and enforcement. Equally important is investing in farmer education and extension services to ensure safe practices are understood and adopted on the ground.
4. Holistic Economic Analysis: Conducting full-cost accounting that internalizes the public health and environmental externalities (both positive and negative) of wastewater reuse to inform truly sustainable policy decisions.

In conclusion, wastewater reuse is not a problem to be solved but a reality to be managed. With a commitment to context-appropriate, multi-faceted strategies that prioritize both economic development and public health, the safe and beneficial reuse of wastewater in agriculture can be a cornerstone of a circular and sustainable water economy.

References

[1] K. Chojnacka, A. Witek-Krowiak, K. Moustakas, D. Skrzypczak, K. Mikula, and M. Loizidou, “A transition from conventional irrigation to fertigation with reclaimed wastewater: Prospects and challenges,” *Renew. Sustain. Energy Rev.*, vol. 130, p. 109959, 2020, doi: 10.1016/j.rser.2020.109959.

[2] G. Butte, C. Niwagaba, and A. Nordin, “Assessing the microbial risk of faecal sludge use in Ugandan agriculture by comparing field and theoretical model output,” *Water Res.*, vol. 197, p. 117068, 2021, doi: 10.1016/j.watres.2021.117068.

[3] N. Rey-Martínez *et al.*, “Combination of technologies for nutrient recovery from wastewater: A review,” *Clean. Waste Syst.*, vol. 7, no. January, 2024, doi: 10.1016/j.clwas.2024.100139.

[4] L. Soler *et al.*, “Characterization of microbial communities and antibiotic resistance in the water–soil–

vegetable interface of a small-scale organic field," *Sci. Hortic. (Amsterdam).*, vol. 345, no. March, 2025, doi: 10.1016/j.scienta.2025.114147.

[5] F. R. Marques, M. E. Magri, I. D. Amoah, T. A. Stenström, and P. L. Paulo, "Development of a semi-quantitative approach for the assessment of microbial health risk associated with wastewater reuse: A case study at the household level," *Environ. Challenges*, vol. 4, no. February, p. 100182, 2021, doi: 10.1016/j.envc.2021.100182.

[6] C. Mejías-Molina, I. Estarlich-Landajo, S. Martínez-Puchol, S. Bofill-Mas, and M. Rusiñol, "Exploring waterborne viruses in groundwater: Quantification and Virome characterization via passive sampling and targeted enrichment sequencing," *Water Res.*, vol. 266, no. June, 2024, doi: 10.1016/j.watres.2024.122305.

[7] K. Haldar, K. Kujawa-Roeleveld, N. Hofstra, D. K. Datta, and H. Rijnaarts, "Microbial contamination in surface water and potential health risks for peri-urban farmers of the Bengal delta," *Int. J. Hyg. Environ. Health,* vol. 244, no. February, p. 114002, 2022, doi: 10.1016/j.ijheh.2022.114002.

[8] T. Sar *et al.*, "Resource recovery and treatment of wastewaters using filamentous fungi," *Sci. Total Environ.*, vol. 951, no. November 2023, p. 175752, 2024, doi: 10.1016/j.scitotenv.2024.175752.

[9] F. J. Vesga, C. Venegas, V. Flórez Martinez, A. C. Sánchez-Alfonso, and A. A. Trespalacios, "Origin of fecal contamination in lettuce and strawberries: From microbial indicators, molecular markers, and H. pylori," *Heliyon*, vol. 10, no. 17, pp. 1–14, 2024, doi: 10.1016/j.heliyon.2024.e36526.

[10] A. Bhambhani, O. Jovanovic, A. van Nieuwenhuijzen, J. P. van der Hoek, and Z. Kapelan, "Introducing a new method to assess the benefits of resources recovered from wastewater to the natural environment," *Sustain. Prod. Consum.*, vol. 46, no. March, pp. 559–570, 2024, doi: 10.1016/j.spc.2024.03.016.