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Risk assessment methods for water resource recovery for the production of bio-composite materials: Literature review and future research directions

A. Nativio[a,*], Z. Kapelan[a], J.P. van der Hoek[a,b]

[a] Department of Water Management, Civil Engineering and Geosciences, Delft University of Technology, Stevinweg 1, Delft, Zuid-Holland 2628 CN, the Netherlands
[b] Waternet, Korte Ouderkerkerdijk 7, Amsterdam 1096 AC, the Netherlands

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ABSTRACT

Bio-composite materials made from resources recovered from the water cycle are the future of the holistic approach towards sustainable wastewater treatment. The raw ingredients for these materials are coming from contaminated sources such as wastewater resources, water plants from surface water etc.. Thus, different risks like human health, environmental and product quality risks need to be assessed. Existing literature was analysed regarding these risks, especially methods concerning the risk assessment in wastewater and drinking water treatment and water/wastewater-based resource recovery for reuse. The reviewed literature identified several risk assessment methods such as FMEA, FMECA, FTA, QMRA and QCRA as frequently used ones for these purposes. However, no dedicated methods were identified for the corresponding risk assessments related to bio-composite materials representing key knowledge gaps. The literature review also showed that the above identified risk assessment methods cannot be directly applied for bio-composite materials as many required input data are missing. To overcome above gaps, future research directions have been identified. These include use of qualitative risk assessment methods such as HAZOP and ETA to first identify hazards and map the risks. Once this is done, QMRA and QCRA could be used in combination with Monte Carlo analysis to assess the actual risks. However, before this can be done, additional work should be carried out to collect the missing data required for the use of these methods in the context of bio-composite materials. In addition, additional experimental work such as column leaching tests should be carried out to assess the environmental risks, in particular, looking at the release of toxic chemical compounds such as heavy metals in the aquatic environment. Finally, a list of quality requirements for bio-composite material and related products (e.g. requirements for mechanical properties, purity of raw materials, etc.) should be made, so that the related product quality risks can be assessed.

1. Introduction

New water smart solutions aiming at improved sustainability, increased resource efficiency, reduced greenhouse gas emissions and based on principles of circular economy are becoming popular and are increasingly developed (Bhambhani et al., 2022; Lam et al., 2020). These include solutions based on various resources recovered from water and wastewater. For example, it is possible to reuse wastewater as a resource and produce energy (Kehrein et al., 2020; van der Hoek et al., 2016), biogas from sludge digestion (Gherghel et al., 2019) or recover raw materials such as bio-fertilizer, bioplastic (Solon et al., 2019), nitrogen (Solon et al., 2019), phosphorus (Devda et al., 2021), struvite (Kehrein et al., 2020), cellulose (Ruiken et al., 2013) and calcite (Schetters et al., 2015). Recovery and reuse of resources from wastewater and water can also have a positive impact on the ecosystem hence providing benefits to both society and nature (Bhambhani et al., 2022).

In terms of reducing negative environmental impact, bio-composite materials are becoming a sustainable alternative on the global market. Bio-composite materials are made from natural ingredients collected from sustainable resources (Roy et al., 2014) like natural fibres from cellulose fibres from crops or waste paper and glued together with a matrix (resin). The use of bio-composite materials will reduce the negative environmental impact compared to the use of composite materials made from polymeric resin and synthetic fibres (Misra et al., 2015). Therefore, these materials can be better alternatives to polymer composite materials made from synthetic fibres (non-renewable resources). Bio-composite materials have found their applications in the automotive, pharmaceutical and food industries (Bharath and Basavarajappa, 2016; Drzal et al., 2001) so far.

Recently, a new type of bio-composite material, made from resources recovered from water and wastewater, is starting to be produced. The raw materials for this new material are recovered from the water cy-

* Corresponding author.
E-mail address: a.nativio@tudelft.nl (A. Nativio).

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cle as follows: (i) calcite pellets recovered as residual product from the drinking water softening (i.e. treatment) process (Schetters et al., 2015); cellulose fibres collected from the toilet paper contained into untreated wastewater treatment and recovered through fine mesh sieving (Ruiken et al., 2013); (iii) natural fibres recovered from grass, reeds and aquatic plants collected during surface water management. Once recovered, these raw materials are glued together with different types of resins. The mixed product is moulded using high pressure and temperature into a bio-composite material. A new material like the one described here can have multiple applications such as building construction elements for riverbank protection, creating nautical signs or elements for building facades.

Having said the above, surface water, raw drinking water and wastewater can be contaminated with pathogens and chemical compounds such as heavy metals, residual drugs, hormones, Persistent Organic Pollutants (POP) and agrochemicals that can potentially make their way into the bio-composite material. It should be noted that environmental toxicity of chemical contaminants (listed above) should be evaluated based on the toxicity of degradation products detected in nature, rather than parent compounds. This applies to chemicals that undergo structural changes as a results of environmental factors. An example of this can be found in the recent study by Remy et al. (2019) where the authors detected levels of chromium as high as 20 mg/kg in the cellulose fibres recovered from the wastewater, i.e. at the level that is ten times higher than the acceptable limits of 2 mg/kg (Washington State Department of Ecology, 2003). If contaminated, the raw materials used to make a bio-composite material can result in several undesirable effects such as workers will be exposed to the pathogens and/or heavy metals during the bio-composite material production via ingestion, inhalation or dermal contact through the dust formed from raw materials. Contaminated raw materials can also pose a threat to the natural environment as these substances may be released into the environment, e.g. via leaching of heavy metals like arsenic, lead and chromium into the river and soil from the river bank protection elements made using the aforementioned bio-composite material. Finally, the contaminated raw materials can also result in a lower quality in terms of mechanical properties of the produced bio-composite material. Given above, it is necessary to assess the human health, environmental and other risks associated with the production and application of bio-composite materials made by resource recovery from the water cycle. For this purpose, relevant risk assessment methods, available in the published literature, were first summarised and analysed. This was done separately for the risks related to wastewater and drinking water treatment plants (Section 2.2) and resource recovery and water reuse (Section 2.3). The applicability of these methods for the production and application of bio-composite materials made by recovering resources from the water cycle is discussed in Section 2.4. The resulting knowledge gaps are presented in Section 2.5. Future research directions to address these gaps are provided in Section 3. Finally, the key findings are summarised in Section 4.

2. Literature review

2.1. Review scope, objectives, and methodology

This scientific review focused on previous studies in which risk assessment methodologies have been developed and illustrated on case studies concerning primarily wastewater and drinking water treatment, followed by cases on resource recovery and water/wastewater reuse.

The aims of the literature review were as follows: (i) identify methodologies developed for assessing risks in **drinking water treatment and wastewater treatment,** and **water/wastewater reuse** and **resource recovery**; (ii) assess the applicability of these methodologies for reuse of resources collected from water to produce **bio-composite materials**; (iii) identify related **knowledge gaps.**

The literature research was performed using Google Scholar, TU Delft repository database and www.scopus.com. Concerning reports about standards, thresholds and methodologies, these were searched using USEPA and WHO websites. Furthermore, technical reports were searched on the STOWA (Foundation for applied water research https://www.stowa.nl/) website.

Relevant papers were identified using keywords such as risk assessment methodologies, water sector, water treatments, w astewater treatments and/or wastewater reuse, resource recovery from water, etc. A total of 19 papers were collected concerning wastewater and drinking water treatment and a total of 14 papers were collected for resource recovery and water reuse.

Once relevant papers were identified, these were critically analysed to first identify the types of risk assessment methods used. The identified methods are shown in Section 2.2 and Section 2.3 respectively for wastewater and drinking water treatment and for resource recovery and water reuse. It was decided to start with risk assessment methodologies applied on wastewater treatment plants (WWTPs) and drinking water treatment plants (DWTPs) as they represent the source water where the raw materials, of our bio-composites, are collected. Then the focus moved on the resource recovery processes and the reuse of water, to obtain an overview of the main potential issues that can be involved in the production of these new bio-composite materials.

The previous studies have been analysed critically and, in more details, to understand the specific aspects of these methods, and how well these methods have been tested/validated on real case studies. Previous studies were analysed and contextualized for the risk assessment methodology applied with the specific case study examined, availability of input data and exposure scenario. Furthermore, several studies were collected in which no risk assessment methodology was applied, but in where an explanation of the way in which raw materials could be recovered from the water sector was provided. These papers proved to be useful to understand what the main hazards and associated risks could be, in terms of human health and environment, during the collection of raw materials from different types of water, such as wastewater, raw drinking water and surface water. Thereafter, in Section 2.4 the methodologies applied in the previous studies are analysed in terms of how they compare to each other, and how these methods can be used to contribute to the knowledge required for the assessment of various risks related to bio-composite materials and their products.

Once the review was completed, key gaps in knowledge were identified by means of further critical analyses and deduction based on the literature review carried out such as which type of methods have been applied in the past, which risks have been assessed so far and what it is missing in literature and why. All of this is compared and reported to the bio-composite case study.

The expected outcome of this review was to find a risk assessment methodology applied in the water sector that can be applied or be adapted to risk assessment for the production and application of bio-composites. The focus was on risks to human health, the environment and water quality, but previous studies in which operational risks were assessed were also evaluated.

2.2. Risk assessment in wastewater and drinking water treatment plants

This section contains a review of previous studies in which risk assessment methodologies were developed for wastewater and drinking water treatment plants. Many authors have used similar risk assessment methods, as the main potential risks appear to be the same (presence of chemical and pathogens in source water). However, each study has important differences both in terms of the input data used, the risk receptors analysed, and finally in terms of the goal of the study. Therefore, it was decided to cite the same studies several times, as they were applied in different areas for different purposes.

Table 1 lists previous studies collected on risk assessment methodologies applied to wastewater and drinking water treatment plants.

Table 1
Summary of risk assessment methodologies for wastewater and drinking water treatment.

Methodology	Reference	Application
Failure Mode and Effects Analysis (FMEA)	Failure modes and effects analysis for cogeneration unit in a wastewater treatment plant (Nazh Gulum et al., 2016)	FMEA is a qualitative risk assessment methodology based on experts ' opinion and literature database. This method finds its applicability mainly on operational risk assessment due to the failure modes of components of a system and/or subsystems. It is not recommended to use this method for human health and environmental risk assessment, unless these are caused by an operational failure.
Modified FMEA: System Modelled Risk Analysis (SMRA) and statistical analysis	A methodology for assessing and monitoring risk in the industrial wastewater sector (Trubetskaya et al., 2021)	As mentioned for FMEA methodology, SMRA finds its application to assess operational failure modes and the related effects. However, the improvements made by authors (e.g. heat map) lead this method to be used for different scenario, but other methods might be preferred for the simplicity of their application.
Fault Tree Analysis (FTA)	Reliability analysis of a wastewater treatment plant using fault tree analysis and Monte Carlo simulation (Taheriyoun and Moradinejad, 2015)	This method is able to identify and quantify the main causes of a first hazardous event. The drawback is in the tree development. The scope of the risk analysis should be defined before to choose the methodology to apply, especially if it is required to study the causes or the effects on an hazardous event.
Bow-Tie (FTA combined with ETA)	Risk assessment of an industrial wastewater treatment and reclamation plant using the Bow-Tie method (Analouei et al., 2019)	This method is recommended if the aim is to analyse causes and effects of a certain hazardous event. At the same time, the application of this method can take more time than expected, especially if there are several first hazardous event to analyse.
Quantitative Microbial Risk Assessment (QMRA) - Guidelines	Quantitative Microbial Risk Assessment: Application for Water Safety Management (USEPA, 1989, 2018; WHO, 2016)	These references concern the guidelines provided by World Health Organization (W.H.O.) and U.S.E.P.A. about the application of QMRA in the water sector. Examples of case studies are provided in these guidelines.
Hazard Quotient (Guidelines)	Risk Assessment Guidance for Superfund Volume I - Human Health Evaluation Manual (Part A) (USEPA, 1989); Human Health and Ecological Risk Assessment (USEPA, 2018)	These references are guidelines published by U.S.E.P.A (U.S. Environmental Protection Agency). These guidelines explain the Hazard Quotient (HQ) method for chemical and microbial risk assessment respectively providing examples.
Hazard Quotient	Bio-aerosols emission and exposure risk of a wastewater treatment plant with A2O treatment process (Han et al., 2019)	HQ method applied to define the microbial risks for human exposure in several contexts. This method can be applied alone or combined with other risk assessment methodology based on the data input availability. HQ is not complete as QMRA is, but it provides all information required in a properly risk assessment analysis.
QMRA & Hazard Quotient	Bio-aerosol in a typical municipal wastewater treatment plant: concentration, size distribution, and health risk assessment (Xu et al., 2020)	QMRA is the most common risk assessment method used to assess microbial risks. This method can be combined with other methodologies, as in this case to HQ in order to obtain more consistent results in terms of probability of infections.
QMRA & Monte Carlo	Quantitative microbial risk assessment and sensitivity analysis for workers exposed to pathogenic bacterial bio-aerosols under various aeration modes in two wastewater treatment plants (Chen et al., 2021)	As mentioned above, QMRA can be combined with Monte Carlo in order to address uncertainties for example due to the lack of consistent input data. This study has proven that the combination of these two methods can provide consistent results and an optimization of normal QMRA.
Multiphasic QCRA	Multiphasic screening of priority chemical compounds in drinking water by process control and human health risk (Liu et al., 2022)	A multiphasic evaluation analysis was carried out in this study to assess health risks due to the presence of toxic compounds. This study represents a novel method and scientific support for Drinking Water Safety (DWS). Furthermore, this method highlights the importance to prevent raw water contamination and enhance removal processes reducing by-products formation by introducing advanced treatment technologies during the purification processes.
Quantitative Chemical Risk Assessment (QCRA)	Development of a quantitative chemical risk assessment (QCRA) procedure for contaminants of emerging concern in drinking water supply (Cantoni et al., 2021)	This new approach has been proven to be efficient concerning the water sector, in particular drinking water treatments. This new approach of QCRA was combined with Monte Carlo resulting in a successful approach highlighting the advantages of a stochastic approach to risk assessment.
RQ and Quality Risk Assessment	Human health risk assessment of heavy metal and pathogenic contamination in surface water of the Punnakayal estuary, South India (Selvam et al., 2022)	QCRA, already mentioned above, has been combined with a quality risk assessment method, in particular using index to quantify the quality of the water. This study has proven the possibility to combine QCRA with other methods different than Monte Carlo, obtaining good and consistent results in terms of human health risks and quality of source water.
Epidemiological study	Faecal indicator bacteria along multiple environmental exposure pathways (water, food, and soil) and intestinal parasites among children in the rural northwest Ethiopia (Gizaw et al., 2022)	Epidemiological study is not a risk assessment methodology, but it can provide good results, also reused as input for risk assessment methodology especially for QMRA and QCRA in terms of human health. The main drawback concerns the availability of input data or previous epidemiological studies performed for a previous outbreak.
QMRA + Monte Carlo method combined with F-N curves	Stochastic modelling of drinking water treatment in quantitative microbial risk assessment (Smeets, 2008)	In this study, the presence of pathogens in raw water and reduction of pathogens with treatment was modelled stochastically with Monte Carlo simulations. Using F-N curve it was possible to assess both variation in risk and the uncertainty. In addition, societal risk calculations can lead to the evaluation of the likelihood of simultaneous infection of a large number of people, referred to as an outbreak.
QMRA combined with epidemiological study	Quantitative microbial risk assessment of distributed drinking water using faecal indicator incidence and concentrations (van Lieverloo et al., 2007)	As already mentioned above, epidemiological study can be combined with QMRA leading to more consistent results and a validation of the QMRA method itself.
QMRA combined with empirical literature data and probability distribution functions (PDFs)	Trends in conducting quantitative microbial risk assessments for water reuse systems: A review (Zhiteneva et al., 2020).	This review summarizes common assumptions in PDF selection for source water and treatment steps and dose-response models for risk assessments applied to two different scenarios. The use of PDFs allowed to assess how the dose-response model choice affects the level of the risks in terms of infection (human health risks).

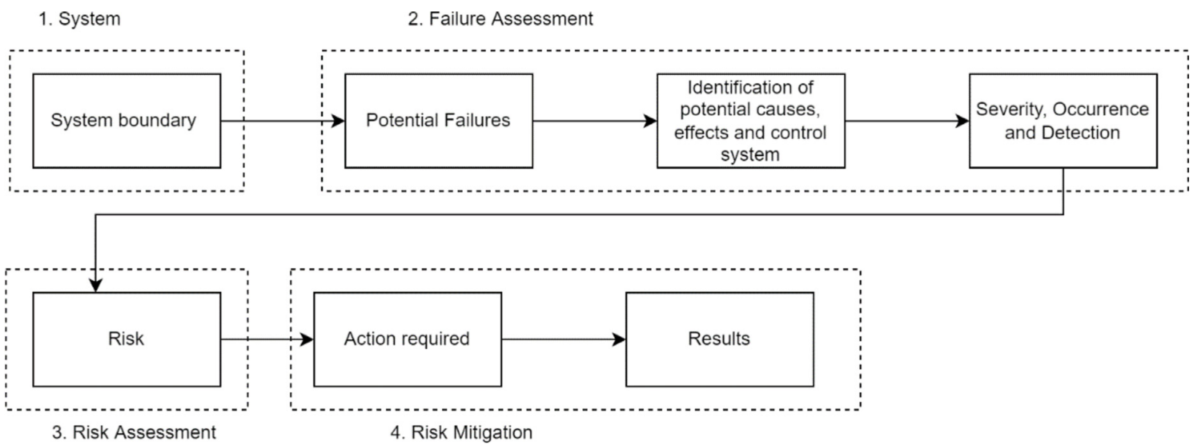

Fig. 1. Scheme to summarise FMEA methodology.

2.2.1. *Risk assessment in wastewater treatment plants*

Wastewater treatment plants (WWTPs) are used to treat wastewater to meet the discharge standards for various applications such as discharge into surface water, direct or indirect water reuse, etc..Risk analysis in wastewater treatment plants is quite important to prevent possible incidents in the treatment processes, as incidents occurring in these plants strongly affect the efficiency and effectiveness of the system and the health of employees (Nazh Gulum et al., 2016).

Evaluating previous studies on risk assessment methodologies applied on WWTPs allows the identification of the main risks involved during wastewater treatment and consequently to recover materials from wastewater like cellulose.

In this section the most relevant references concerning risk assessment methods used in WWTPs were analysed. The main risk assessment methods found in literature are as follows:

- FMEA: Failure Mode Effects Analysis;
- SMRA: System Modelled Risk Analysis;
- FTA: Fault Tree Analysis;
- Bow Tie;
- QMRA: Quantitative Microbial Risk Assessment;
- HQ: Hazard Quotient.

The first four risk assessment methods were used focusig on operational risk assessment, however, in WWTPs, as well as DWTPs, there are also other type of risks. In fact, when looking at human health risks and natural environment, the main two risk categories associated with these water treatment plants are microbial and chemical risks due to the presence of pathogens and chemical contaminants in the untreated water.

Failure Mode Effects Analysis (FMEA). FMEA is used to detect and prevent possible incidents in system based on experts' opinion and system databases which record failures that have occurred in the same or similar systems (Lipol and Haq, 2011). This qualitative risk assessment methodology is commonly applied to prevent operational issues. Fig. 1 provides a scheme of how FMEA methodology works. Nazh Gulum et al. (2016) used this methodology to prevent possible incidents in cogeneration system of a wastewater treatment plants. Wastewater treatment plants require huge amounts of thermal and electrical energy and some of this energy can be provided from cogeneration plants (Nazh Gulum et al., 2016). The authors applied the FMEA methodology by calculating the RPN (Risk Priority Number) which consists of attributing values scaled from 1 to 5 in three different categories to a specific event. The categories are: (i) severity (impact/effects of the event), (ii) detectability (possibility to detect the failure) and (iii) occurrence. The experts attribute a value for each category defining failure modes/effects and report them in a table.

One of the main drawbacks of this method is that it is not able to define the combination of failures that lead to the first hazardous event (defined as event that occurs when an hazard is realized), resulting in a harm (Center for Chemical Process Safety, 1999). Also, this method may only identify major failure modes in a system (Lipol and Haq, 2011). Furthermore, the FMEA method requires a detailed knowledge of the system and its devices/equipment, including their response to the failure which is not always available.

Even though quantitative risk assessment methodologies are usually preferred, the qualitative risk analysis methodologies such as FMEA can provide a clear overview of what the main process criticalities are. Furthermore, FMEA methodology proved to be an effective method to assess operational risks arising from failures of devices and/or system, as it has been demonstrated with the study carried out by Nazh Gulum et al. (2016). There is extensive use of both design and process FMEAs inside the automotive, aerospace, medical, nuclear and other manufacturing industries (Lipol and Haq, 2011).

System Modelled Risk Analysis (SMRA). SMRA is a methodology developed by Trubetskaya et al. (2021) in order to address the risks associated with the industrial wastewater treatment plants. In this study the authors decided to perform the risk assessment in a closed loop as shown in Fig. 2.

Focusing on the risk assessment stage, a modified FMEA (SMRA) has been applied by the authors to prioritizing the risks, as an improvement of the traditional FMEA (Trubetskaya et al., 2021). The SMRA consists in 7 steps:

1 Identification of potential Failure Mode;
2 Description of potential Effects;
3 Calculation of a β coefficient (that quantifies the effects);
4 Determine the USL (Current Process Control) using literature;
5 Sensitivity analysis of parameter causing any associated risks;
6 Calculation of RPN;
7 Fill out FMEA form.

Concerning the last step, the form was filled out using a colour scale from green (low risk) to red (highest risk), as it is usually done with the Risk Matrix (see Section 2.2.2). The importance of this work consists in a development of a new risk assessment framework able to predict and minimize the risks at WWTPs, improving the traditional FMEA methodology. In addition, the authors have highlighted that the risk assessment carried out with this type of risk assessment methods needs to be improved with additional tools like heat map, statistical analysis, sensitivity analysis, etc. This methodology, as well as FMEA, are type of risk assessment methods specific for assessing operational risks and failure modes. Thus, these are not the best recommended methodologies for assessing other risk categories like human health and/or environmental risks unless these are caused by an operational failure mode.

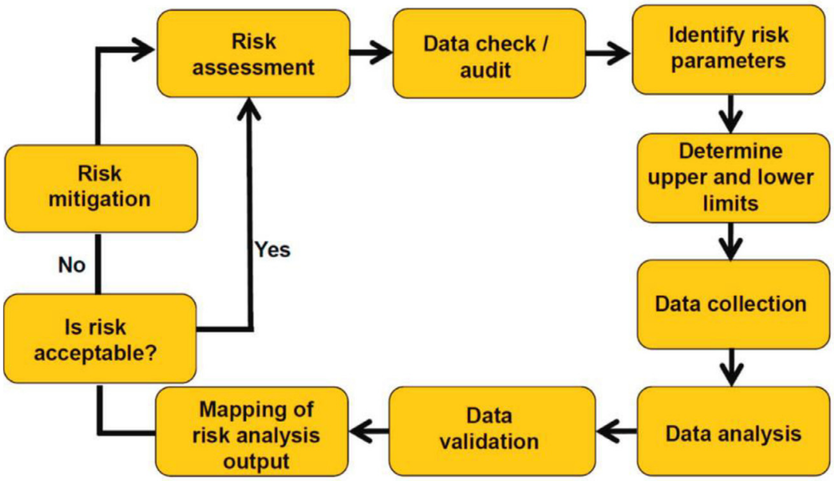

Fig. 2. Developed framework with modified FMEA (SRMA) for risk assessment for industrial wastewater treatment (Trubetskaya et al., 2021).

Fault Tree Analysis (FTA). FTA is another common risk assessment method that can be applied both qualitatively and quantitatively. This methodology is commonly used to define the causes behind an occurred incidents defining the probability of occurrence of an incident. This method can also be applied preventively in the design phase of the system, identifying the potential causes based on Boolean algebra of an incidents finding also the possible solution and mitigation measures. Taheriyoun and Moradinejad (2015) applied the FTA combined with Monte Carlo method to assess the reliability of wastewater treatment plants: the Top Event considered for the FTA is the violation of the allowable BOD (biological oxygen demand) effluent concentration. Monte Carlo method was used to simulate the occurrences of the primary event (Top Event).

FTA allows the frequency of the occurrence of the Top Event (first hazardous incident) to be estimated, using a logical model of the system failure mechanism. The use of this method begins with the definition of the Top Event and then all causes will be defined from the top to the bottom of the tree. The starting point to build the tree is the upper part (Top Event) and the end point is the lowest part of the tree and the events at the last level of the tree are called “bottom events”. This means that analysts must be familiar with the system and its possible failures. In order to link and combine the failures of several basic components of the system, logic gates (AND, OR) are used.

FTA finds its applicability mainly in the chemical process industry, and it is used for addressing safety and reliability (Center for Chemical Process Safety, 1999). Moreover, this method is also able to identify human errors during an industrial process, and its use is not limited for operational risks. The main weakness is related to the development of the tree, and there is a potential for error if failure paths are omitted, also changing the results of the analysis. This method requires considerable experience to generate useful, well-structured trees in a reasonable period. The choice to use this methodology will depend on the scope of the risk assessment: if the aim is to define the main causes that lead to the first hazardous event, this is the best suitable methodology to proceed with. On the other hands, if the purpose of the risk assessment is to address the consequences due to the occurrence of a first hazardous event, other methodologies (e.g. Event Tree Analysis) are recommended. As mentioned above, the main drawback of this methodology concerns the development of the tree, so before to choose if this method is suitable or not it is preferable to clarify the objective of the risk assessment.

Monte Carlo approach is a stochastic method and is one of the most effective methodologies for reliability assessment due to its ability to express well the statistical nature of events (Center for Chemical Process Safety, 1999; Taheriyoun and Moradinejad, 2015). This approach is a mathematical technique, which is used to estimate the possible outcomes of an uncertain event. Monte Carlo Simulations have assessed the impact of risk in many real-life scenarios, such as in artificial intelligence, stock prices, sales forecasting, project management, and pricing. They also provide several advantages over predictive models with fixed inputs, such as the ability to conduct sensitivity analysis or calculate the correlation of inputs. Sensitivity analysis allows decision-makers to see the impact of individual inputs on a given outcome and correlation allows them to understand relationships between any input variables (IBM Cloud Education, 2020). Taheriyoun and Moradinejad (2015) have proven the effectivity of the combination of these two methods for assessing the reliability of wastewater treatment plants and, in particular, for the reuse of the effluent for irrigation. Indeed, the object was to define the major failure modes in terms of quality of effluent, determining which failure modes can occur, focusing on operational issues of the system.

Bow-Tie. This method was applied by Analouei et al. (2019) with the aim of assessing health risks and other adverse impacts of wastewater treatment. The Bow-Tie method consists of a combination of the above described FTA and Event Tree Analysis. The latter is an inductive risk assessment methodology able to identify the main effects from an occurred hazardous event (Marhavilas et al., 2011; Center for Chemical Process Safety, 1999).

An example of the scheme of the Bow-Tie method is illustrated in Figure 3 where the first hazardous event (Top Event) is placed in the centre from where two tree diagrams are constructed. On the left the tree diagram is represented by the FTA, this part is also referred as *prevention*, since the basic event (Bottom Event) leading to the Top Event are identified. Therefore, by assessing the causes it would be possible to prevent the occurrence of the Top Event. The tree diagram on the right side is represented by the ETA and corresponds to the *risk map* and *mitigation* phase. In this way the possible effects (scenario) are identified and by evaluating these it would be possible to reduce the negative impacts. The Bow-Tie method results the best complete risk assessment method to apply, if the aim is to analyse causes and effects of a certain hazardous event. At the same time, the application of this method can take more time than expected, especially if there are several first hazardous event to analyse, as it is for bio-composite materials.

The main drawbacks of the Bow-Tie methodology are as follows: (i)experience and knowledge of the system by the analysts (for both methods), strong dependency on experts‘ opinion (for both methods), (iii) presence of potential for error if failure paths are omitted (FTA), (iv) identification of all effects from first hazardous event, including failure of safety barriers.

Quantitative Microbial Risk Assessment and Quantitative Chemical Risk Assessment. There are several risk assessment method-

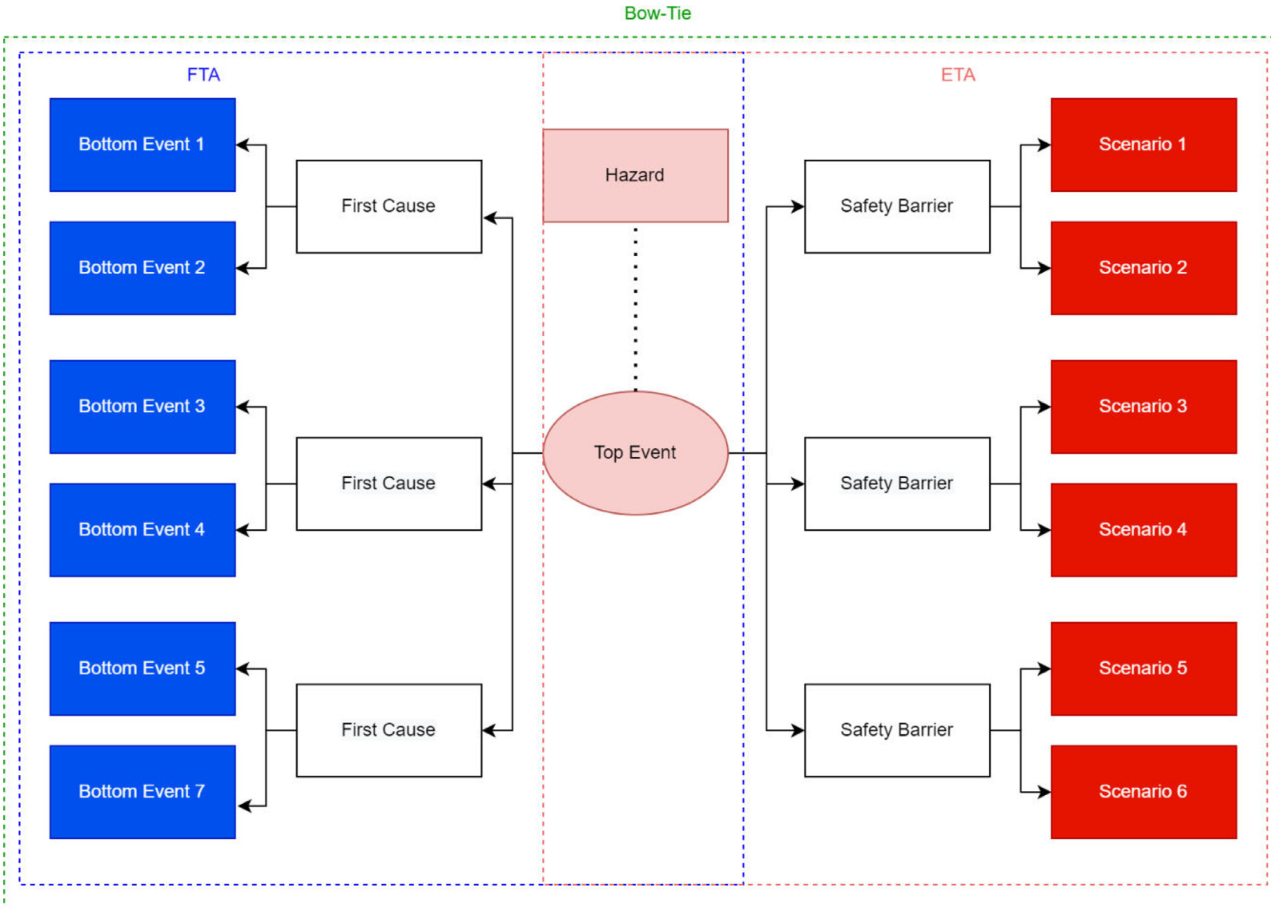

Fig. 3. Scheme of a typical FTA, ETA and Bow-Tie methodology.

ologies to assess microbial and chemical risks, starting with the common qualitative risk assessment methodologies such as Check list and Risk Matrix to the quantitative risk assessment methods like FTA and ETA. In addition to the common methodologies, Quantitative Microbial Risk Assessment (QMRA), of which a detailed description is provided by WHO (2016) and also by Bassett et al. (2012), is specifically used to quantify the level of human health risks due to the presence of pathogens. Whereas, chemical risks are assessed by using the Quantitative Chemical Risk Assessment (QCRA) described by USEPA (1989, 2009).

QMRA methodology is a quantitative risk assessment approach that combines scientific knowledge about the presence and nature of pathogens, human exposure and the health effects that may result from the exposure (WHO, 2016). This methodology is organised in four steps: (a) Hazard Identification; (b) Exposure Assessment; (c) Dose-Response Assessment; (d) Risk Characterization. In the last stage, risks are quantified in terms of probability of infection/illness.

QMRA is often combined with other methodologies such as deterministic modelling, using probabilistic density functions (PDF), more suitable for a specific case, to assess the exposure to the microorganisms or the dose-response relationships (WHO, 2016). However, as it is possible to notice in the studies mentioned below, in most cases microbial risks cannot be assessed by using only a deterministic model due to uncertainties related to the type of pathogens, their concentration and uncertainties in predicting exposure and dose-response relationships. Therefore, QMRA is usually combined with a stochastic model, in particular the Monte Carlo method.

Hazard Quotient. Another common methodology for assessing microbial risks is the Hazard Quotient (HQ) method based on U.S.E.P.A. guidelines (Xu et al., 2020). This is a risk assessment methodology that consists of calculating the ratio between the average daily dose rate and the allowed reference dose which is likely to be without an appreciable risk of deleterious effects during a lifetime (USEPA, 1993). This ratio must be less than 1 to consider the risk acceptable. This method, is typically also used for assessing chemical risks, which guidelines are provided by (USEPA, 1989).

The QMRA and HQ methods have been also combined when assessing some specific risks such as the risk of bio-aerosol formation at WWTPs (Xu et al., 2020). Exposure to bio-aerosols is one of the main risks that affects workers and nearby population since it results in exposure to microorganisms from sewage sludge. Bio-aerosol generated from WWTPs may contain *Legionella pneumophila*, fungi and other airborne bacteria. In this study the QMRA was used in order to assess the probability of infection and illness, defining a dose-response model. The HQ was used for evaluating if the microbial risk. Han et al. (2019) applied the HQ method in their study. The objective of their work was to evaluate the seasonal variation of the health risks due to the human exposure to the bio-aerosol formed from untreated wastewater. In order to carry out this study, several species of pathogens have been found in bio-aerosol such as *Chryseobacterium, Stenotrophomonas, Alcaligenes, Micrococcus, Pantoea, Enterobacter and Escherichia-Shigella*, increasing the risk of exposure from bio-aerosol (Han et al., 2019). In contrast, a different approach was followed by Chen et al. (2021) combining the QMRA with Monte Carlo method to assess the health risks for workers exposed to *S. aureus* or *E.coli* bio-aerosol in two different WWTPs. In this study, Monte Carlo method was used to assess the variability and uncertainty of QMRA method input values.

Based on the previous studies mentioned above, QMRA is the most common methodology for assessing microbial risks.

This method takes into account all components of the water system, providing valuable information on the effects of each component on the human health risks from exposure to waterborne pathogens (WHO, 2016). The limitation of this method is related to the availability of the data on presence, transport, and removal of pathogens in water treatment processes. When the data are absent, QMRA has to work with assumptions (WHO, 2016), so analysts must have experience in this area.

2.2.2. Application of risk assessment methods to drinking water treatment plants

In the previous section the published literature has been reported, focusing on the risk assessment methodologies applied in wastewater treatment plants. In this section the focus is on the risk assessment methodologies applied in drinking water treatment plants.

The World Health Organization (WHO) has developed the Water Safety Plan (WSP) (WHO, 2016) to achieve safe drinking water through proper control of drinking water sources, treatments and distribution. The capacity of the total system to provide safe drinking water and the activities required to verify water safety are assessed in the WSP since even a short period of unsafe drinking water can have a great impact on the risk of infection to human health (Smeets, 2008). With regard to drinking water treatment, the focus on risk assessment is about human health risk, in terms of chemical (Quantitative Chemical Risk Assessment) and microbial risks (Quantitative Microbial Risk Assessment), both described in the previous section. The main risk assessment methodologies found in literature are as follows:

- Accumulation Index & Hazard Index;
- Quantitative Chemical Risk Assessment & Hazard Quotient;
- Quantitative Microbial risk Assessment.

Accumulation Index & Hazard Index. Liu et al. (2022) carried out a multiphasic criteria to assess the health risk, due to the presence of toxic compounds in drinking water, by considering drinking water treatment efficiency and effluent quality, including carcinogen classification based on the International Agency for Research on Cancer standards (as carcinogenic risks), accumulation index (AI), and hazard index (HI) as the multiphasic evaluation variables. In this study several samples were collected both from the influent (raw water) and effluent and analysed chemically. Then, quantitative chemical risk analysis was performed with the aim to assess health risks. To summarize the results the authors made a heat map of the priority of chemical compounds for both raw and treated water with the aim of colour-coding the heavy metals found to be harmful to human health. The difference between raw and treated water implies that many chemicals can be removed during the drinking water treatment, but by-products were generated during disinfection processes (Liu et al., 2022). This study represents a novel method and scientific support for drinking water safety (DWS). Furthermore, the authors highlighted the importance to prevent raw water contamination and enhance removal processes reducing by-products formation by introducing advanced treatment technologies during the purification processes.

Quantitative Chemical Risk Assessment & Hazard Quotient. QCRA & HQ methodologies proposed by (USEPA, 1989) consists to calculate the daily intake dose (exposure assessment) selecting a specific exposure pathway such as ingestion, inhalation or dermal contact. Once the daily intake dose is calculated, this value is compared to the reference allowed dose (RfD) for ingestion and dermal exposure (USEPA, 1993) or to the reference allowed concentration (RfC) for inhalation exposure (USEPA, 1993), by dividing the daily intake dose by RfD/RfC. This ratio is called Hazard Quotient (HQ) (Risk Characterization). If the HQ is lower than 1, the risk can be considered acceptable, otherwise measures to reduce the risk are required (USEPA, 1989). In order to define the total risk, the single calculated HQ (based on exposure pathways) are summed calculating the Hazard Index (HI) (USEPA, 1989).

QCRA in drinking water treatment plants is mostly applied to investigate the amount of heavy metals in source water (e.g. surface or ground water) and to assess whether that may be toxic for human health. Cantoni et al. (2021) developed a new method for assessing chemical risks in drinking water treatment and supply. They proposed a new probabilistic procedure of the QCRA, with the aim to assess potential health risks associated with the presence of contaminants of emerging concern (CECs) in drinking water. The QCRA estimates the probabilistic distribution of CECs concentrations in drinking water based on their concentration in source water and simulating the breakthrough curves of a granular activated carbon (GAC) treatment process (Cantoni et al., 2021). This new methodology was combined with the Monte Carlo method, resulting in a successful approach highlighting the advantages of a stochastic approach to risk assessment. The method developed by Cantoni et al. (2021) is based on Hazard Quotient described by USEPA (1989): the daily reference dose was calculated by estimating the Drinking Water Target Level (DWTL), which represents the concentration of a compound that does not result in the exceedance of the tolerable exposure (e.g. RfD) of a consumer over lifetime (Cantoni et al., 2021).

Selvam et al. (2022) investigated the change in the amount of toxic heavy metals in the river system during the COVID-19 pandemic. The Hazard Quotient (HQ) method was applied, including the carcinogenic risk assessment for both children and adults through ingestion and dermal adsorption exposures. Samples were collected both in pre-lockdown period (28-29 January 2020) and during the lockdown (6-7 May 2020). Finally, the HMPI (Heavy Metal Pollution Index) was evaluated providing a classification of heavy metal pollution in surface water bodies into three categories such as low contamination (HMPI<15), medium contamination (HMPI=15-30) and high contamination (HMPI>30) with the aim of assessing water quality. To assess human health risks the Chronic Daily Intake (CDI) was calculated for ingestion and dermal contact respectively and then divided by the Reference Dose (RfD) in order to define the hazard Quotient (HQ). The final step was to calculate the Hazard Index (HI) by summing the HQ for ingestion and dermal contact of a specific heavy metal. Toxic metals with HQ and HI greater than 1 may have adverse effects on human health. The same procedure was applied to assess carcinogenic risks by calculating the CDI and multiply it by the Safety factor (SF) to define the Carcinogenic Risk (USEPA, 2007). The acceptable value for carcinogenic risk is in the range $10^{-6} - 10^{-4}$. The importance of this study concerns the assessment of water quality by calculating the amount of pollution due to the presence of toxic heavy metals. Furthermore, the combination of a quantitative methodology such as Hazard Quotient to assess human health risks with a procedure to assess quality risks, using the results as input for QCRA, was validated.

Quantitative Microbial Risk Assessment (QMRA). With regard to microbial risk in drinking water systems, the concentration of pathogens is usually below the detection limit, but a QMRA is still necessary to assess the safety of the drinking water supply. The QMRA method is already described in Section 2.2.1 hence this section shows and discusses applications of this method to drinking water systems.

Gizaw et al. (2022) in their study carried out a cross-sectional study for households with children in the rural village of Ethiopia. The potential for external exposure of children to intestinal parasites was assessed by determining the presence of faecal indicator organism (*E. coli*) in drinking water. The exposure was also monitored using a questionnaire to assess behaviours that result in high risk of exposure. No common risk assessment methodologies were applied in this study, but the epidemiological study was conducted to assess the risk of exposure, especially for children. This methodology did not provide a level of risk of infection but was able to assess exposure to faecal contamination in drinking water. Epidemiological studies are often carried out to obtain input data for performing QMRA, sometimes the QMRA is carried out and the outputs are compared with the results of an epidemiological studies.

Smeets (2008) monitored the presence of pathogens in raw water and the reduction of pathogen by treatment was stochastically modelled using Monte Carlo simulations. This method was tested in a case study with Campylobacter monitoring data from a rapid sand filtration and ozonation process. The results lead to an overestimation, so an improved method was developed by using complementary cumulative distribution function (CCDF) graphs, combining with a stochastic approach. The results were then presented in frequency number curves (F-N curves) (Smeets, 2008). Using F-N curves is useful in terms of risk assessment, since it is possible to visualize graphically the frequency of the incidents and the related number of people involved. This method is usually applied for building construction risk assessment after the Event Tree Analysis application, but it can be applied in different context if all data are available.

Microbial risks in drinking water treatment were also carried out by van Lieverloo et al. (2007), by applying the QMRA methodology for distributed drinking water. In order to estimate the infection risk, the cumulative probability density function (CDF) was used. In this study, the concentrations of faecal contamination, such as E.coli, Campylobacter, enteroviruses and other faecal indicators, were used to estimate the infection risks to consumers in the affected areas (van Lieverloo et al., 2007).The results indicated that the infection risks may be very high, especially from Campylobacter and enteroviruses, but also that the uncertainties are significantly high.

Zhiteneva et al. (2020) carried out a review summarizing common assumptions in statistical distribution selection for dose-response models for risk assessments applied to potable and non-potable reuse scenarios. The objective was to evaluate the evaluate how the dose-response model choice affects the level of risks. The benefit of using PDFs for describing concentrations is that it allows a more comprehensive assessment of final risks (Zhiteneva et al., 2020). For many waterborne bacteria such as *Legionella, Escherichia coli*, rotavirus, fungi, the dose-response relationship is provided in literature (QMRA Wiki, 2017).

2.3. Risk assessment methods for water/wastewater reuse and resource recovery

This section focuses on the review of methods used for assessment of risks related to the reuse of water/wastewater and resource recovery. A summary of the applied methods in the studies exanimated in this section is listed in Table 3.

Concerning the resource recovery, only a few references have been found regarding risk assessment methodologies. Most of the previous studies in literature focus on recovery processes, the quality of the recovered materials and their potential reuse. Only some of them focus on the main human health problems resulting from resource recovery from water, but no risk assessment methodologies have been applied. Examples are Hammes et al. (2011) who studied the microbial contamination of calcite pellets, Remy et al. (2019) who focused on chemical contamination with residual drugs and heavy metals of cellulose fibres collected from wastewater treatment plants, and Tang et al. (2019) who studied the chemical contamination such as heavy metals of calcite pellets collected from different drinking water treatment plants. Although risk assessment methodologies were not applied in these studies, they are a useful tool to understand what the main issues are during collection of raw materials from water, and that the recovery process and the reuse of these materials can lead to various risks, especially for human health.

In this section, as already done in the previous sections, the collected references are listed starting from qualitative and semi-qualitative risk assessment methodologies, followed by the hybrid methodologies (if there are) and finishing with the quantitative risk assessment methods. This section is focused firstly on resource recovery process, then on water reuse. The main risk assessment methodologies found in literature are as follows:

- FMECA: Failure Mode Effects and Criticality Analysis;
- IWSQI: Irrigation Water Security Quality-based Index;
- Risk Matrix;
- QMRA: Quantitative Microbial Risk Assessment;
- QMEA: Quantitative Microbial Exposure Assessment;
- RQ: Risk Quotient;
- QCRA&HQ: Quantitative Chemical Risk Assessment & Hazard Quotient.

FMECA. Schetters et al. (2015) applied the Failure Mode Effects and Criticality Analysis (FMECA) for the transition from garnet sand to calcite in the drinking water pellet softening process. All possible failures of process elements in the water and the seeding material stream were evaluated according to their effects on water quality, safety, and environment. The FMECA methodology used by Schetters et al. (2015) is an improvement of conventional FMEA method applied by Nazh Gulum et al. (2016) and mentioned in Section 2.2.1. The FMECA method is composed of two separate analyses: the FMEA and Criticality Analysis (CA) (Headquarters, 2006). The RPN calculation is one of the benefits of the FMECA method, as it is able to prioritize (qualitatively) issues for corrective action starting with the worst failure mode to the mildest (Lipol and Haq, 2011).

The benefits of using FMECA are mainly in the outputs: this method can identify potential failure modes for an individual product or process, rank the failure modes and quantify the effects. On the other hand, as already mentioned in this methodology is entirely dependent from the experience of the analysts. In addition, this method is not suitable for multiple failures, as in the case of larger systems.

IWSQI. The rising of the population leads to increase of water demands of all aspects of water uses, including agricultural, so this implies the research of new sources of water. The reuse of water includes the verifications of "Water Security Index" to reflect the water use sustainability. Demerdash et al. (2022) developed the IWSQI method that is suitable for defining a sustainable irrigation water system in Egypt. This security index considers both the water quantity and quality. If the parameter causes harm for a specific indicator, it is given an objective index value of zero, otherwise a value of 1. The probability of harm was used in the risk assessment and the results of this study showed water insecurity that needs to be improved. In this study no common risk assessment methodologies were applied, but the risk was assessed by evaluating the quality and quantity of water sources for irrigation.

By assessing the quality of the source water, it is possible to predict the potential contamination in terms of chemicals and pathogens that might be present in the resource recovered from the source water. This is a useful tool in case consistent input data for carrying out a risk assessment are missing, and the analysis must be based on assumptions. In that case, the assumptions can be made by using data of source water, where the materials/resources are collected.

A similar approach based on the analysis of water samples and comparison of them to the European standards, has been carried out by Bonetta et al. (2022). In this study, the aim was to investigate the role of wastewater treatments in microbiological contamination by evaluating the possible risks associated with wastewater effluent reuse, considering new EU legislation (2020/741) on minimum requirements for water reuse. Objective of this study was to assess the human exposure to the microbial contamination: all samples were analysed for total *Coliform, Enterococci, E. coli* and *Clostridium perfringens* spore counts. Then, a statistical analysis was performed to define the concentrations of pathogens. The results were compared with the EU thresholds (Bonetta et al., 2022). This study showed the risk of exposure to the pathogens according to the type of treatments carried out in different WWTPs, highlighting which treatment seems to be the best for achieving the requirements proposed by new European regulations. This is critically important to prevent the possible microbial risk to public health.

Table 2
Risk Matrix and 5 categories of risks based on colour code.

Severity	Catastrophic	5	10	15	20	25
	Significant	4	8	12	16	20
	Moderate3	3	6	9	12	15
	Low2	2	4	6	8	10
	Negligible	1	2	3	4	5
Catastrophic [16-25] = STOP		1	2	3	4	5
Unacceptable [15] = URGENT ACTION						
Undesirable [8-15] = ACTION						
Acceptable [4-6] = MONITOR		Improbable	Remote	Occasional	Probable	Frequent
Desirable [1-3] = NO ACTION		Likelihood				

Risk Matrix. Talking about the reuse of wastewater, in particular for irrigation, Elgallal et al. (2016) used a risk matrix methodology in order to assess environmental and health risks associated with the presence of chemicals in wastewater used for irrigation. This study shows that inappropriate management of wastewater irrigation can contribute to serious environmental and health problems. The risk matrix ranks on a scale from 1 to 5, the occurrence and severity of a specific event according to the experts 'opinion. Table 2 shows the five categories of risks: Catastrophic (Deepnarain et al., 2020); Unacceptable (orange); Undesirable (yellow); Acceptable (light green) and Desirable (green).

Risk Matrix is probably the most common risk assessment method used in literature. This method provides a semi-quantitative risk characterization, since it can rank the risks based on two important categories: (i) occurrence of a dangerous event; (ii) severity of effects of the occurred dangerous event. The risk is indeed calculated as product of likelihood and severity ($R = L\ x\ S$) (Marhavilas et al., 2011).

This method provides a general overview of the main risks involved in a system or subsystems, but it is strongly dependent on experts 'opinion and the availability of literature data or record database of previous incidents. However, some case studies require the application of quantitative risk assessment method, so the Risk Matrix is commonly used also as preliminary qualitative risk analysis before the quantitative methodologies are applied.

QMRA. Looking at quantitative risk assessment methodologies applied in resource recovery and water reuse, Mara et al. (2007) assessed the human health risks associated with the use of wastewater for crop irrigation in two different scenarios (unrestricted and restricted irrigation) using standard QMRA combined with Monte Carlo method. The results were compared with the output of an epidemiological study. The study was focused on human exposure to the rotavirus and *E. coli.* The infection risks estimated by Monte Carlo simulations from 10,000-trials generally showed relatively good agreement (no more than one order of magnitude) with epidemiologically determined incidences. On the other hand, the assumptions made for QMRA calculations were close to the conditions in the epidemiological field studies (Mara et al., 2007). This study gave satisfactory results when the analytical risk assessment methodology, QMRA in this case, was compared with an epidemiological study. Epidemiological study is not a risk assessment methodology itself, but it is a useful tool to measure the proportion of infected people in an exposed group compared with a control group, measuring the incidence of disease. QMRA quantifies the infection risk in an exposed group.

The weakness of using an epidemiological study compared to the QMRA concerns the availability of consistent input data. Therefore, the feasibility of a combination of QMRA and epidemiological study is highly dependent on the case study, where at least the epidemiological study must have already been carried out.

A similar study was conducted by An et al. (2007) who investigated human exposure to *E. coli* in reclaimed wastewater irrigation, considering two types of scenarios: (1) wastewater treated with UV disinfection; (2) wastewater treated without UV disinfection. In this study the QMRA was applied, defining the dose-response model by applying B-Poisson model to estimate the microbial risk of pathogen ingestion among farmers and nearby children (An et al., 2007). This methodology was combined with Monte Carlo simulations (10,000 trials). The results of this study showed that water treated with UV disinfection significantly reduced microbiological risks. The main problem to use this disinfection treatment concerns the costs because this treatment requires a large amount of energy. In addition, UV disinfection is effective in killing microorganisms, but it does not work for chemical removal. It can also be ineffective in killing microorganisms if not used appropriately.

QMRA has also been applied to investigate the microbial risk of *E.coli* and rotavirus in treated wastewater for different applications such as irrigation, landscape, industry and urban non-potable water. Persson and Liu (2014) have evaluated if the treated water after tertiary treatment combined with a pond system could be reused for different applications from a microbial point of view. Also in this case, the QMRA was combined with Monte Carlo method, which is based on statistical sampling techniques to produce a stochastic approximation of the result and evaluate the uncertainty surrounding estimated values represented by credibility intervals (Persson and Liu, 2014).

QMEA. Allende et al. (2018) proposed QMEA as an alternative approach to the use of QMRA, to assess the impact of different surface water sources as irrigation water and seasonality on the *E. coli* load of field-grown leafy greens. One of the limitation of QMRA concerns the limited availability of microbiology models describing the behaviour of these pathogens in agricultural settings (Allende et al., 2018). The authors proposed this new approach for assessing the contamination of *E. coli* during the production of baby spinach, evaluating the potential impact of weather conditions. The results were analysed by using @Risk software (extension of Microsoft Excel) able also to assess the variability of pathogens based on seasonality. The effective of this new approach concerns the focus on the Exposure Assessment, without investigating on the risk characterization. The results of this model are valid input data for both other risk assessment methods and epidemiological study. Furthermore, the QMEA can also assess the impact of safety measures provided for different risk mitigation strategies. Another potential output of this model might also be the assessment of the impact of safety measures provided for different risk mitigation strategies.

RQ. Authors such as Adegoke et al. (2018) have investigated the microbial risk for farmers, their family and consumers, due to the use of wastewater effluent for irrigation. The aim of this paper was a review of the previous epidemiological studies and health risks associated with the reuse of wastewater for irrigation. The risk assessment was carried out considering the different routes of exposure and the characteristics of the individual who became ill. The risk was characterized by applying the RQ method also known as Hazard Quotient (HQ) (see Section 2.2), proposed by USEPA (1989). The ratio is measured is calculated between the measured concentration of antibiotic (MEC) in wastewater and the predicted no effect concentration (PNEC) (Adegoke et al., 2018). If RQ $<$ 0.1 the risk is low, 0.1<RQ<1 means medium risk and RQ>1 means high risk (Adegoke et al., 2018). This study assessed not only human health risk, but also environmental risk due to the antibiotic residues and their impact. The authors improved the RQ method from the original assign-

Table 3
Summary of risk assessment methodologies used for water/wastewater reuse and resource recovery.

Methodology	Reference	Application
FMECA: Failure Mode Effects and Criticality Analysis	Circular economy in drinking water treatment: reuse of ground pellets as seeding material in the pellet softening process (Schetters et al., 2015)	The application of FMECA for this specific case study concerns the identification and assessment of operational risks during the softening process. The comparison of the results with those of a different risk assessment methodology is useful to compare the two methods and evaluate the pros and cons according to their application to the specific scenario assessed.
Irrigation Water Security Quality-based Index.	Development of a quality-based irrigation water security index (Demerdash et al., 2022)	Water Security Index is not a proper risk assessment methodology, but in this study the application of this method has provided good results in terms of potential hazards and human exposure to the contaminants. In addition, it is useful to evaluate the quality of source water when input data for risk assessment are missing.
Microbial risk assessment on wastewater effluent reuse	Impact of wastewater treatment plants on microbiological contamination for evaluating the risks of wastewater reuse (Bonetta et al., 2022)	In this study no risk assessment methods were applied, but disinfection treatments of wastewater were evaluated in terms of efficiency in order to assess the exposure and potential risks for human health. This kind of studies are useful when consistent input data for risk assessment are missing, and assumptions might be made as results of water quality assessment.
Risk Matrix	Assessment of potential risks associated with chemicals in wastewater used for irrigation in arid and semiarid zones: A review (Elgallal et al., 2016)	Risk Matrix in this study has proven to be one of the most effective qualitative risk assessment methods. In fact, Risk Matrix, unlike the FMEA and FMECA, provided a risk map in terms of operational, human health and environmental risks.
QMRA combined with Monte Carlo and comparison with epidemiological study	Health risks in wastewater irrigation: Comparing estimates from quantitative microbial risk analyses and epidemiological studies (Mara et al., 2007)	This study demonstrated the effectiveness of the combination of QMRA and epidemiological study, validating the QMRA method itself. The main disadvantage of this combination concerns the feasibility of carrying out or using an existing epidemiological study combined with QMRA, due to the lack of consistent input data from a previous outbreak (needed for the epidemiological study and outputs comparison for QMRA validation).
QMRA and Monte Carlo	Estimating the Microbial Risk of E. coli in Reclaimed Wastewater Irrigation on Paddy Field (An et al., 2007)	QMRA was carried out in this study with the aim of assessing the human health risks as a result of exposure to *E. Coli* in reclaimed wastewater irrigation. The method was combined with stochastic approach to estimate the risk associated with uncertainties. UV-disinfected irrigation water showed a lower risk value than others. The main problem concerns the amount of energy requirement (and costs) to use UV-Disinfection treatment.
QMRA	Estimating microbial risk in treated wastewater for reuse: a case study in Lund, Sweden (Persson and Liu, 2014)	QMRA has been applied to estimate the microbial risk of E. coli and rotavirus in treated wastewater for different reuse. The QMRA as already mentioned is the best method for assessing microbial risk quantitatively. In this case the method provided also a good first estimate of where an increased risk may occur for the different modes of water reuse practices.
QMEA (Quantitative Microbial Exposure Assessment)	Quantitative microbial exposure modelling as a tool to evaluate the impact of contamination level of surface irrigation water and seasonality on faecal hygiene indicator E. coli in leafy green production (Allende et al., 2018)	This study describes QMEA as an alternative approach to the general QMRA method when the necessary data are lacking. One of the outputs of this method was the verification that the selection of irrigation water sources affects E. coli loads in leafy vegetables at harvest. Another potential output of this model might also be the assessment of the impact of safety measures provided for different risk mitigation strategies.
Review of Epidemiological studies and Risk Quotient	Epidemiological Evidence and Health Risks Associated With Agricultural Reuse of Partially Treated and Untreated Wastewater: A Review (Adegoke et al., 2018)	The authors improved the RQ method from the original method assigning different risk levels based on the parameters considered to calculate the risk quotient. The introduction of different risk index levels is an improvement of the method that considers different risk mitigation strategies, which might now be specific according to the level of risk as a result, perhaps also leading to a reduction in costs in terms of risk mitigation measures.
Quantitative Chemical Risk Assessment – Health Risk Index (RHI) and hazard Index (HI)	Heavy metal contamination and risk assessment in water, paddy soil, and rice around an electroplating plant (Liu et al., 2011)	This methodology is an improvement on the HQ method proposed by USEPA (1989), where in this case the authors used different terminology (which is more specific than the original) and assigned different risk levels. In addition, in this specific case study, the importance of having different risk levels concerns a better assessment of the consequences for human health and consequently also a reduction in costs in terms of risk mitigation measures.

ing different risk levels based on the parameters to calculate the risk quotient. In the original method the risk was considered acceptable or not by assigning the value 0 and 1 respectively. The introduction of different risk index levels is an improvement of the method that considers different risk mitigation strategies, which can now be specific according to the level of risk as a result, perhaps also leading to a reduction in costs.

QCRA&HQ. Liu et al. (2011) assessed the chemical risks of heavy metal contamination in paddy soil due to irrigation with reclaimed wastewater. The risk assessment was carried out by collecting samples from sites upstream (control) and downstream of the electroplating wastewater outlet. Electroplating wastewater means the wastewater that comes from the surface plating operations. The metal is dipped in an electroplating solution of various types of metals and then rinsed. It originates from washing, rinsing, and batch dumps. The technological processes of electroplating wastewater treatment are classified according to the reactions and chemical composition of the electrolytes, which are the source of wastewater forming (Muratov et al., 2020). Risk assessment code was used to evaluate the environmental risks of heavy metals in soils. The health risk index and hazard index (HI) were calculated to assess potential health risks to local populations through rice consumption. In this study the focus was on concentration of heavy metals such as Cu, Cr, Ni, Pb and Cd in water, paddy soils and rice. If RAC is <1%, the soil is not at risk to the environment. Low risk, medium risk, high risk, and very high risk are associated with RAC values of 1–10%, 11– 30%, 31–50%, and >75%, respectively. The HRI was calculated as the ratio of estimated rice exposure to the oral reference dose. The HI is a measure of the potential risk of adverse health effects from a mixture of chemical constituents in rice. This value is the sum of all HRIs for a specific receptor/pathway (e.g. ingestion). This methodology is an improvement on the HQ method proposed by USEPA (1989), where in this case the authors used different terminology (which is more specific than the original) and assigned different risk levels. Looking at the Risk Matrix, there are 5 risk levels divided into different colours according to the severity of the consequences and the probability of occurrence. In this specific case study, the importance of having different risk levels concerns a better assessment of the consequences for human health and consequently also a reduction in the costs of safety barriers during the risk mitigation phase.

2.4. Potential application of risk assessment methods for bio-composite materials

As already mentioned in Section 2.1, the bio-composite materials considered in this paper are completely new as they are made from resources recovered from the water sector. Therefore, with the aim of finding the best suitable methodology for risk assessment on the bio-composite production process and the application of these materials, this review was carried out looking at risk assessment methodologies applied in the water sector (wastewater treatment, drinking water treatment, resource recovery and water/wastewater reuse). Some of the risk assessment methodologies applied in studies concerning the water sector cannot be directly applied for bio-composite materials as most of the required input data are missing such as the amount of pathogens and/or heavy metals contained as impurities in the raw materials. Therefore, assumptions and analysis have to be performed, since these data are not available in literature. This affirmation concerns the applicability of ETA, QMRA and QCRA. As far as other risk assessment methodologies are concerned, these can be applied for the risk assessment of the production and application of bio-composite products based on the available data and the objective of the risk analysis. The following sections describe if (and how) these methodologies (listed in Table 4) can be applied for bio-composite production process and application, including their pros and cons.

2.4.1. Semi-qualitative risk assessment methodologies

FMEA and FMECA are two semi-quantitative methodologies based on experts‘ opinion and literature database. These methodologies find their best applicability in operational risk assessment, identifying potential failures and their effects (Marhavilas et al., 2011).

Looking at the bio-composite materials, objective of this paper, the FMEA methodology could find its application with regards to the manufacturing processes like raw materials recovery processes, mixing process and moulding to obtain the bio-based product, looking for potential operational risks. The application of this method for bio-composite materials risk assessment will provide an overview of the main potential operational failure modes, without assessing the other risks in terms human health and environment, unless they are caused from a failure mode. Thus, other methodologies to assess these risks will be required and the risk assessment framework might be not easy to develop. In conclusion it is possible to affirm that this methodology is not the best suitable risk assessment method to use for the purpose of the human health and environmental risk assessment for bio-composite materials.

Risk matrix is a semi-qualitative methodology, which requires the experience of the analyst to rank from 1 to 5 (Table 2), the probability of occurrence of a specific hazardous event and its severity. This method could be applied to the production process of bio-composites, including the process of collecting raw materials. Risk matrix is able to classify outcome risks regardless of the type of risk (human health risk, quality risk or environmental risk). The limitation of the applicability of this method is mostly based on experts ‘ opinion and literature database and as mentioned above, these materials are completely new, so no references are available. However, the Risk matrix might be applied to assess the potential environmental risk due to the application of the bio-composite product by referring to similar incidents in the literature due to the release of toxic substances to the environment, in particular release of heavy metals into aquatic environment.

2.4.2. Hybrid risk assessment methodologies

Fault Tree Analysis (FTA), Event Tree Analysis and Bow-Tie methods are defined as hybrid methodologies since these methods can be applied both for qualitatively and quantitatively risk assessment. The choice of FTA rather than ETA depends on the purpose of the risk assessment: if the objective of the risk assessment is prevention then FTA is the most appropriate methodology. Otherwise, if the objective of the risk assessment is protection, the ETA is the best choice. In both cases, depending on the availability of data to perform a full quantitative risk assessment, the Bow-Tie methodology might be the best choice, as this method is able to define the causes and effects of the Top Event, quantify the probability of occurrence of the Top Event (solving FTA stage) and the effects (solving ETA stage). Looking at the case study of this paper, bio-composite materials, the purpose of the risk assessment protection. The risk assessment will be performed by evaluating and assess the consequences of reusing materials recovered from the water cycle to produce bio-composite materials and the effects of the application of related products in terms of human health, quality of materials and environmental impact.

Thus, Event Tree Analysis seems to be the most suitable methodology for qualitative risk assessment in order to obtain an overview (map) of the main risks involved during the collection of raw materials and then for the bio-composite production process. ETA can also be applied quantitatively, depending on the available data and the type of risks mapped by the qualitative risk analysis. In fact, for each type of risk there is a methodology that is best suited to assess the specific risks (e.g. QCRA and QMRA). Therefore, the FTA and Bow-Tie methodologies do not appear to be the most appropriate methods for carrying out risk assessment for the production and application of bio-composite materials.

2.4.3. Quantitative risk assessment methodologies

Quantitative Microbial Risk Assessment (QMRA) and Quantitative Chemical Risk Assessment (QCRA) are the quantitative risk assessment methods found in literature concerning risk assessment in water sector and resource recovery.

The applicability of these methodologies for assessing chemical and microbial risks are valuable tools for defining and assessing risks to human health and environment.

QMRA. Looking at the bio-composite materials, the main issues (described in Section 1) related to the production and applicability of the new bio-composite materials are focused on the potential chemical and microbial contamination of the raw materials and consequently of the bio-composites themselves. With regards on microbial contamination, QMRA is so far the best risk assessment methodology that can be applied for bio-composite materials risk assessment, especially in terms of human health risks. In fact, workers may be exposed to these contaminants in different exposure routes such as ingestion, inhalation and dermal contact. Exposure can be caused by the dust formed by the raw materials. The main issue with this method concerns the availability of input data, but as mentioned above this method works with assumption quite well. Thus, input data can be collected from the raw material producer (e.g. provided safety data sheet) or field studies of the source water and making assumptions. Once the amount and type of pathogens present in the raw materials are known/assumed, it would be possible to calculate the probability of illness through the dose-response model. Finally, the risk can be characterized in terms of the probability of infection. The uncertainties due to the lack of consistent input data might be addressed by combining QMRA with Monte Carlo stochastic approach.

In previous study described above, the QMRA is sometimes combined with epidemiological study for both validate the QMRA methodology and also to assess the dose-response model. Concerning the new bio-composite materials it is not possible to perform epidemiological studies

Table 4
Summary of literature review regarding risk assessment methodologies for drinking water and wastewater treatment.

Methodology	Risks	Topic	Applicability for bio-composites
Qualitative: FMEA	Operational risks	Wastewater treatment plant	FMEA is usually applied to assess operational risks of a system or component of a system in the design phase. This method can be applied for bio-composite materials case study, with regard to their manufacturing process focusing on the potential failure modes of the equipment required for both raw materials recovery process and bio-composite product production (e.g. mixer and compression moulding machine), but it is not indicated to assess human health, quality and environmental risks, unless they are caused by a specific operational failure mode.
Semi-quantitative: FMECA	General risks	Resource recovery from drinking water: calcite pellets	FMECA, as already said for FMEA, is a methodology usually applied to assess operational risks. As already said for FMEA this method might be applied for bio-composite materials risk assessment looking at operational risk and failure modes that can lead to a human health and/or environmental risks (e.g. failure of safety protocols risk of cut or abrasion for workers and release of toxic compounds in water system).
Semi-quantitative: Risk Matrix	Health and environmental risks	Resource recovery from wastewater: reuse of wastewater	The risk matrix is a methodology that can be applied for risk assessment on bio-composite production and use. Considering that the materials are completely new, no historical data or records of previous incidents are available. Thus, it would be preferable to apply this method in specific case where it is possible to refer a similar previous incidents reported in literature.
Quantitative: FTA & Monte Carlo	Operational risks	Wastewater treatment plant	FTA is a valuable tool for assessing risks both qualitatively and quantitatively by defining the causes of the Top Event and its frequency of occurrence. The objective of this methodology is to prevent the occurrence of a such dangerous event (TE[a]). When considering risk assessment for the production and application of bio-composite materials, the objective of which is to assess human health and environmental risks, this method is not the best choice. Indeed, the objective of risk assessment on bio-composites is to assess the consequences of the occurrence of TE.
Quantitative: Bow – Tie	Operational risks	Wastewater treatment plant	The Bow-Tie methodology is one of the most complete risk assessment methodologies as it can assess the causes and effects of a single first hazardous event. The aim of this method is to define the main causes and effects of a system at the same time resulting in one of the most exhaustive methodologies to apply for risk assessment. In this case study, as explained above, FTA is not applicable for the purpose of this paper, so Bow-Tie method results not the best choice as well.
Quantitative: QMRA	Microbial risk	Wastewater treatment plant and wastewater reuse	QMRA method can be applied to assess microbial risks due to the potential contamination of raw materials. The exposure might be via different exposure routes and the dose-response model can be defined by using QMRA. If input data are missing, assumptions might be made and assessed by combining QMRA with stochastic approach (e.g. Monte Carlo method).
Quantitative: Epidemiological study	Microbial risk	Resource recovery from water cycle: reuse of wastewater	Epidemiological study is not a valid tool for assessing human health risks associated with the production and application of bio-composite materials, as these materials are completely new, no references and record of previous incidents are available.
Quantitative: QCRA and Hazard Quotient	Chemical risk	Drinking water treatment plant	General QCRA represents the tool to assess quantitatively chemical risks in a certain system, including bio-composite production and application. This method may also be combined with a stochastic approach (e.g. Monte Carlo method) in order to assess the uncertainties due to the lack of input data (or lack of consistent input data) and enhance the assumptions made to assess the exposure.

[a] TE: Top Event of the FTA

for two main reason: (i) no available data in literature concerning infection from bio-composite materials contaminated with pathogens; (ii) no outbreaks had occurred so far because of the production and application of these new materials.

QCRA. QCRA finds its application in several sectors with appropriate changes based on the specific case study. With regards to the bio-composite materials, this method can assess chemical risks in terms of both human health and environment. Indeed, the presence of the chemicals is not dangerous only for human exposure, but also for the environment. The main chemical pollutants present in the raw materials concern heavy metals. Therefore, some input data such as potential ingestion and inhalation rate, RfD and RfC are available on the guidelines and safety data sheet provided by U.S.E.P.A.. To support what mentioned above, the previous studies present in literature mentioned above and in Sections 2.2 and 2.3, have proven that the HQ is the best methodology to assess chemical risks in water sector, especially when combined with a stochastic approach to assess the uncertainties associated with exposure assessment when consistent input data are not available and assumptions had to be made. Furthermore, chemicals contamination might have also negative effects on environment. An example can be the application of bio-composite product as river bank protection and the potential release of chemicals into the aquatic environment might lead to negative environmental effects. Thus, a specific risk assessment methodology for assessing chemical risks is required.

2.5. Summary of key review findings

The existing risk assessment methodologies proved to be effective for assessing human health (e.g. microbial and chemical risks), water quality, environmental and also operational risks in wastewater and drinking water treatment and also in water/wastewater reuse and resource recovery.

Since the bio-composite materials are new, existing human health, environmental and quality risk assessment methods and tools used in drinking water treatment, wastewater treatment, water/wastewater reuse and resource recovery have not yet been studied for their applicability to bio-composite materials. Thus, it is still difficult to define the most suitable risk assessment methodology for production of the bio-composite materials and their application. However, some suggestions are provided in Table 4.

Outputs of this review can be summarised in the following key knowledge gaps:

1 Not many studies exist on risk assessment related to water/wastewater based resource recovery. Some of these methods could be potentially used to assess the risks associated with the extraction of raw materials required for the production of new bio-composite materials but it is unclear if and how these methods could be used / modified to serve that purpose;

2 No methods nor studies for the specific assessment of human health risks associated with new bio-composite materials and related products have been found in the literature. Some existing methods have the potential to be used for this but it is unclear if and how these methods could be used / modified to enable new application;
3 No methods nor studies for the specific assessment of environmental risks associated with bio-composite materials and related products have been found in the literature. Some existing methods have the potential to be used for this but it is unclear if and how these methods could be used / modified to enable new application;
4 No methods nor studies for the specific assessment of quality risks for bio-composite materials and related products have been found in the literature. Some existing methods have the potential to be used for this but it is unclear if and how these methods could be used / modified to enable new application.

The identified knowledge gaps can be summarised as the need for a solid risk assessment framework capable of assessing the human health, quality and environmental risks associated with the production and application of bio-composite materials. The framework should be able to perform a complete risk assessment from the hazard identification stage, through the risk mapping and finally the risk quantification. Each risk must be assessed using a specific methodology.

The proposal of this framework is described in Section 3, as a direction to address the identified knowledge gap.

3. Future research directions

3.1. Knowledge gap 1: existing risk assessment methodologies for water-based resource recovery are limited

Several resources are recovered from the water cycle, with the aim of reusing them for producing energy, bio-fertiliser, industrial application, nutrients recovery etc. (Devda et al., 2021; Ruiken et al., 2013; Schetters et al., 2015; Solon et al., 2019; van der Hoek et al., 2016, 2019). From these studies it was possible to assume that the main risks associated with the recovery of resources from the water sector concern human health risk (in terms of microbial and chemical risk), but also environmental risk and quality of the recovered materials. Therefore, a framework to assess risks associated with water based resource recovery is required. One of the most important steps to start with is a preliminary qualitative risk assessment for hazard identification and risk mapping. The objective of qualitative risk analysis is to define the main hazards and the associated risks. The latter must be mapped and categorized in order to define the best suitable methodology based on risk category. The qualitative risk assessment should be carried out starting from the resource recovery process, then the risk assessment should focus on the production of bio-composite material (as intermediate product) and finally the focus should be about the final product and its application (e.g. river bank protection). Then, specific quantitative risk assessment methodologies will be applied based on the risk type (see Sections 3.2, 3.3 and 3.4).

Hazard identification in the case of biocomposite materials and related products might be conducted by applying one of the qualitative or semi-quantitative risk assessment methodologies applied in previous studies such as FMEA, FMECA or Risk Matrix. However, as mentioned in Section 2.4.1 these methodologies are not the best choice to assess qualitatively risk related to human health, quality and environemnt for bio-composite production process and application, but they find their best applicability to detect and assess operational failures. Furthermore, the main challenge of assessing risks associated with the production and application of bio-composite materials concern the input data that are missing.

In relation to the above, it would be preferable to use a methodology that is structured, methodical and possible to apply when potential hazards are only assumed and not really known. One of the methodologies that might best suit this case study is Hazard & Operability (HAZOP), which is usually applied for hazard identification and qualitative risk assessment (Center for Chemical Process Safety, 1999). The HAZOP methodology was not applied in the previous studies found in literature, but it seems to be a better solutions to carry out the hazard identification stage for bio-compoiste production process. The HAZOP methodology is usually applied at the first stage of the design process, where hazards and associated risks are not really known, in this way this method is able to provide an overview of the main hazardous events that can occur during the process analysed.

Once the list of all potential process deviations with their potential causes and effects has been made, it is possible to create a map of risks. To characterize the risks, the Event Tree Analysis might be one of the best methodology to apply, as it can be used both qualitatively and quantitatively (Marhavilas et al., 2011). As decribed in Section 2.2, the ETA is a structured and inductive methodology that can define the effects of an hazardous event, taking into account the intermediate incidents and the safety barriers (both their functionality or their failure) (Rausand, 2015). At this stage, it would be interesting to have a map of the all risks associated with the process of recovering resources from water cycle. It would also be valuable to categorize the risks according to the type of risk (e.g. environemntal risk human health risk and quality risk), in order to have an overview of what would be the best suitable methodology for quantitative risk assessment.

3.2. Knowledge gap 2: risk assessment methodologies to assess health risks associated with new bio-composite materials and related products are missing

In Section 3.1, we explained the importance of carrying out a qualitative risk assessment methodology to define the main hazards and risks associated with recovering resources from the water cycle, in order to reuse them for bio-composite production. Once the raw materials have been collected, what would be the main risks to human health originating from the production process of the new bio-composites and from the use of products made from this bio-composite material?

Outputs of qualitative risk assessment might be analysed in terms of type of risk. Concerning human health risks, one of the main expected results of the qualitative risk assessment conerns the presence of pathogens and chemicals. Thus, QMRA and QCRA might be carried out to assess risks associated with the reus of raw materials to produce bio-composite and the application of the bio-based products.

Concerning QCRA, as already mentioned in Table 4, the Hazard Quotient (HQ) would be the most suitable methodology to assess chemical risks related to the production and application of the bio-composite materials. The potential chemical contaminants, in particular for raw materials, concern heavy metals. Therefore, the major risk would be the human exposure to these contaminants via three potential pathways (ingestion, inhalation and dermal contact) through the dust formed from the raw materials. The input parameters, needed to characterize the risk, such as RfD, RfC, ingestion and inhalation rate, exposure duration, etc. are provided by U.S.E.P.A. guidelines to assess chemical risk (USEPA, 1989, 1993, 2009).

QMRA, as mentioned in Table 4, can be applied to assess micorbial risk during the production process of bio-composite materials and their application. This methodology is described by WHO (2016) that provides Guidelines with several examples of the application of this methodology in the water sector. The input parameters such as the distribution to simulate the dose-response model for a specific group of pathogens is given in online database by QMRA Wiki (2017).

As already mentioned, the main issues to perform a risk assessment on bio-composite materials, concern the availability of input data, in paticular those regarding the concentrations of pathogens and/or chemical compunds in the raw materials. One of the solutions to this issue might be the use of safety data sheets provided by the suppliers of the raw materials or referring to literature data about the quality of source water where these materials are collected. In addition, QCRA, as well as QMRA, might be combined with a stochastic apporach (e.g. Monte Carlo method), to assess the uncertainties related to the assumptions made due to the unaviability of consistent input data in order to assess the exposure.

Another solution to get consistent input data can be provided by physically and chemically analysing the raw materials prior to their application. This experimental work can provide more details about the concentration of pathogens and chemicals in the raw materials and what kind of disinfection treatment could be applied to obtain a raw material with higher purity. These analyses should be done by the producer and this information should be shared with the research team in order to define which type of risk assessment method should be performed according to the type of risk present (e.g. chemical or microbial). Knowing the actual amount of chemicals (as well as of pathogens) reduces the uncertainties linked to the exposure assessment and leads to more consistent results.

3.3. Knowledge gap 3: there are no risk assessment methodologies to assess environmental risks associated with new bio-composite material and related products

Outputs of qualitative risk assessment, described in Section 3.1, show the type of risks involved in the production process of bio-composite materials and their application. One of the risk type resulted conerns the environmental risk.

Environmental risks, unlike the health risks, concern mainly the related products of bio-composite material ahd their application in the natural environemnt. An example of this is the river (or canal) bank protection element made from new biocomposite material and installed in the natural (aquatic) environment. If the raw materials used for the production of bio-composite material that these elements are made of are contaminated, certain toxic substances (e.g. chemical compunds) could be released to the environment. For future research, it would be interesting to carry out leaching tests. Leaching assessment procedures have been used to determine the leachability of heavy metals as input for evaluating the risk from sewage sludge compost land application (Fang et al., 2017).

The application of these tests on samples of bio-composite material aims to simulate the leaching of inorganic and organic compunds (e.g. heavy metals and/or organic micropollutants) and to assess the corresponding environmental risks. Furthermore, bio-composite materials with different compositions should be analysed, in order to compare different materials and see which one results in lower leaching in the aquatic environment.

Output of leaching tests is the amount of chemicals, in particular heavy metals, that are released from the bio-composite mnmaterial and leach into the environment. These values can be used as input for Environmental Risk Assessment (ERA). The ERA can be done by using quantitative Event Tree Analysis based on availability of data (e.g. frequency of first hazardous event and intermediate events) or also using the Risk Matrix that classifies risks according to experts' opinion. The application of the risk matrix may be effective if the effects of the application of bio-composite materials (e.g. canal bank protection) are compared with previous similar incidents such as the release of toxic substances into the aquatic environment due to the application of the bio-based product. This may be a better solution if the data necessary to perform a quantitative ETA are missing.

The results of leaching test can also be used as input for assessing human health risks related to the application of the bio-composite materials by knowing their leaching behaviour. Furthermore, it should also be interesting to assess the environmental risks due to the transport of raw materials to the bio-compoiste factory and the environmental impact related to the recovery process.

3.4. Knowledge gap 4: there are no risk assessment methodologies to assess quality risks for bio-composite materials and related products

Other outputs of qualitative risk assessment may concern quality risks, in particular quality of materials in terms of mechanical properties, purity, etc..

Quality risks are different from human health and environmental risks, because before starting to assess quality risks the quality concept must be defined (UNI-EN-ISO-9001, 2015). As bio-composite materials are new and their applications are not fully known, quility requirements are not yet well defined. Looking at how these materials are made, and the potential applications ranging widely from river/canal bank protection elements to bulding facade elements and road traffic signs, one of the quality requiremnts might be related to the mechanical properties. For those bio-composite products, whose application is in the outdoor environment, an example of quality requirements might be resistence to adverse climatic conditions and impacts. Another example of potential quality requirement could be in terms of the purity of raw materials used for the production of bio-composite, since the presence of contaminants as impurites can reduce the adhesion with other ingredients (e.g. resin) and reduce the mechanical properties of the bio-composite product. Therefore, a list of quality requirements, related to the application of the bio-composite material, should be provided and then it should be checked whether the requirements are met by the new bio-composite materials.

Once the list of quality requirements is made, these could be evaluated by the ETA application. The Event Tree analysis, as described above, is able to logically define the effects for each hazardous event, defining the potential risk scenario. ETA can be applied both qualitatively and quantitatively to address quality risks of biocomposite materials: qualitatively it is possible to define the worst case scenario due to non-compliance with the list of quality requirements, quantitatively it is possible to quantify the probability of occurrence of each intermediate event and related scenario starting from the first hazardous event. If no data are available to perform a quantitative risk assessment, the risk matrix can be applied, ranking the risk level according to expert opinion.

4. Conclusions

Bio-composite materials made from resources recovered from the water sector are new and they are just starting to be produced and used in The Netherlands and other countries. Given that raw resources for the production of these materials are coming from sources with potential contaminants (e.g. wastewater treatment), their use may lead to potential human health risks, environmental risks and product quality risks.

Previous studies regarding the assessment methods for these types of risks in the water sector were identified and reviewed. In particular, related methods concerning the risk assessment in wastewater and drinking water treatment and water/wastewater based resource recovery for reuse were analysed. No dedicated methods were identified for the assessment of human health, environmental and quality risks related to the production (and application) of bio-composite materials representing the key knowledge gaps.

Despite above some of the existing, more general risk assessment methods seem to have a potential to be used to assess the above risks and have been identified as possible future research directions. For example, the HAZOP method could be applied/adapted to perform the qualitative risk assessment, i.e. to identify key hazards and map the associated risks using the qualitative Event Tree Analysis method. Once the key risks are mapped and categorized, QMRA and QCRA methods could be used to assess the actual microbial and chemical risks to human health. Before this can be done additional work should be carried out to collect the missing information required for the use of QMRA and QCRA methods in the context of bio-composite materials. Stochastic approach could also be adopted in order to take into account the uncertainties associated with limited input data available which is likely to prevail in the future. With regard to the risks posed to the natural environment, it is clear that additional field and laboratory work needs to be conducted to help with the assessment of this risk category. For example, column leaching tests could be carried out to assess the risks related to uncontrolled release of toxic chemical compounds such as heavy metals into the aquatic environment and soil. Finally, a list of quality requirements for bio-composite product (e.g. specific requirements for mechanical properties, purity of raw materials, shape, etc.) has to be made, so that the related material quality risks can be assessed.

Our future work will focus on the development of above three risk assessment methods and related experimental work.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Data availability

No data was used for the research described in the article.

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