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Introducing Eco-gamma: A novel environmental impact index for water quantity and quality evaluation

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INDEX

1 Summary

The main motivation of this work is the creation and proposal of a new index that measures the environmental impact of water quality degradation. There are many methods that currently assess impacts based on the quantity of water consumed or some specific effects on human health but not a transversally accepted method for the change in water quality due human or natural pollution. The first chapter of this report is the introduction to the subject and background information supporting the main ideas. It is established that the property the index will be developed from is the growth rate of the living forms inhabiting an aquatic environment.

Then, a summary of the literary review performed is presented in chapter 2. The most relevant findings of the review are the gamma concept and the cardinal model, both which are later used as the basis for the index development, called Eco-gamma due its inspiration in the gamma concept. This chapter is complemented with the description of different properties of the water that may affect the growth rate of their living forms and a list of possible pollution sources.

Next chapter is the index development, where some relevant parameters are characterized from the previous review, which are needed to be included in the form of the cardinal model adopted. A back-up for temperature and other typical variables is set. After that, the index mathematical expression is presented, along with a discussion of its most relevant characteristics. Finally, categories of impact are defined according to the possible values of Eco-gamma index.

Chapter 5 corresponds to the application of the index. It includes a basic example together with a more complex problem. All the assumptions are explained, which are typical tasks in real life applications.

The closure chapter of conclusions has final discussions about the index and mentions possible guidelines and future tasks to improve and expand the index basis and applications of this work.

2 Introduction

The main environmental concerns nowadays are related to energy and water. As the world`s population demand continues growing, larger amounts of usable water to satisfy the different humanity needs are required. The vast majority of the water is salty, while the immediately available fresh water must be channeled to wherever it is needed. However, extracting resources from nature has several impacts, reason for changing towards a circular economy behavior, decreasing the usage of natural water to the minimum and creating a cycle within the human activities. Discarded water by some actors, which is polluted, may be useful in other processes.

Currently, the environmental impact of the water usage is estimated based mainly in the amount of water consumed (*water footprint*), with a minor emphasis on water quality degradation. There are several methods for the measurement of a water usage index and different approaches for the water footprint including Life Cycle Assessment (Barroso 2019). However, there is no transversally accepted method to perform a water quality impact evaluation. Precisely, the LCA provides information through the life of a product, but not an environment impact. What does exists are indices that measure somehow the current state of the quality of water based on various parameters (Borges, et al. 2018). Many methods offer categories of impact over human lives due toxicity or exploitation, but not directly about the degradation of the water itself. The degradation of quality is according to the legislation that allows to use the water for a certain human activity, instead of living organisms from the source the water source is extracted or where it is naturally poured.

A body of fresh water can be considered polluted if a stream of salt water is pouring on it. The same is truth for the opposite case, it is, a stream of fresh water pouring on a body of salt water, because it changes the *natural* salinity of this water, thus promoting or inhibiting the development of certain species. Pollution should be considered as the change in any parameter of the normal conditions of the environment, being possible that the alteration of certain conditions are in benefit for some species rather than other ones. In this case, not only the amount of water must be considered, in the process of extraction for example, but also its quality of the source. The greater the difference to the normal conditions, the greater the resulting impact.

The goal of the work explained in this report is to develop a characterization of the impact on a body of water when any of its properties are modified. To do this, a particular or a set of characteristics must be chosen to relate the impact on the environment to a measure variable.

Initially, the concept of exergy and its derived eco-exergy were considered. Exergy is calculated as the capacity of a system to produce work, when a certain variable (for example, temperature) moves away from a reference level. The eco-exergy provides a measure of the resources retrieved from the environment or lost from society to nature. A small amount of a chemical compound with a great toxicity produce a low resources loss (eco-exergy) but a great impact on the living organisms. By being able to compute the exergy of a system through all the variables that can deviate from its normal conditions, an impact index of the environment could be created. Despite some interesting properties of this concept, it was ruled out in favor of another characteristic, which is a more direct form of representation and easier to measure. The chosen property is the growth rate of the living forms that inhabit a bounded ecosystem, which is easier to measure and relate to external factors that can accelerate, decrease or inhibit it.

An ideal method to evaluate the impact should be as general as possible. Each species has different unique characteristics that will allow them to survive in certain conditions and will adapt differently to the variation in their environments. However, their tolerance living values are a consequence of adaptation to the environment in which they live, whose general conditions are measurable and traceable over time. So, based on the species behavior, a general evaluation index will be proposed. This will be called Eco-gamma.

This index will include the impact on the attributes of quantity and quality of the involved masses of water. The reasoning behind the use of the growth rate parameter is explained, along with their characteristics. The advantages and method of application will be described as well.

3 Literature Review and background

A literary review is made in order to acquire updated knowledge and references for this work. The following sections explain the main findings and how they can be used.

For variations in the growing rate of any organism, especially microbial life, most of the studies included in the review belong to the food industry field. The idea behind these investigations is trying to determine the extreme living conditions of certain species that usually interfere with food preservation. For this reason, is particularly relevant to obtain, for example, inhibition temperatures and to manipulate other characteristics of the media where the microorganisms are being grown that can have influence over them. It is easier and more direct to study growth dynamics in this way, in a controlled environment, rather than measure in directly in the field. However, the governing phenomena are essentially the same, allowing the possibility of proposals and conclusions based in this information. Further analysis will be discussed at the conclusions.

3.1 Gamma Concept

A certain environment and the species living on it can be affected by several factors. A first approach would be the modeling of each factor and the interactions between them and then the total effect on every organism or the environment. However, this could be incredibly complex and may need powerful mathematical tools just to get simple basic results. So, when the effects over a particular species need to be modeled, the *gamma concept* or *gamma hypothesis* is used. This assumption simplifies the problem, indicating that the different environmental factors have separate effects, allowing to work independently on each one, and accounting the combined effect only at the end. The concept was first introduced by McMeekin et al (1987) and later formalized as the gamma hypothesis by Zwietering et al. (1993).

Precisely, a typical use of the gamma hypothesis is the study of how the growth speed of a microorganism is affected by the variation of its environmental conditions. Examples of this can be found applied in several studies (Leroi, et al. 2012, Akkermans, et al. 2017, Coroller, et al. 2015), where each factor is modeled separately, and finally the multiplication of the numerical representation of all of them counts as the desired model. Other advantage of this approach is that can easily integrate additional variables to the existing model that may have not used initially.

Mathematically, the gamma concept may be represented by equation (1):

$$\mu_{max} = \mu_{opt} \prod_{i=1}^{r} \gamma_i(X_i) \tag{1}$$

Where μ_{opt} is the *optimal* growth rate (T^{-1}), and μ_{max} is the *maximum* growth (T^{-1}) rate at a certain value of γ. In the expression, $\gamma_i(X_i)$, is the numerical number of a gamma coefficient i for a variable X_i, from a total of r variables considered.

3.2 Modeling responses

There exist several environmental factors that may affect microbial growth. The most important and usually explored are temperature and pH, but the analysis can be extended to salinity, pressure or other. For each variable, different methods to analyze the impact have been developed, resulting in different equations trying to reproduce the observed behaviors.

3.2.1 Temperature

The effect of temperature on the growth of microorganisms is the most explored and researched environmental factor. Several equations have been proposed, starting with variations of the Arrhenius equation for the kinetic of chemical reactions, proposed in the 19th century.

$$k = Ae^{\frac{-E_a}{RT}} \tag{2}$$

Where k is the rate constant (s^{-1}), A is the collision factor (s^{-1}), E_a is the activation energy ($Jmol^{-1}$), R is the universal gas constant (8.314 $Jmol^{-1}K^{-1}$), and T is the absolute temperature (K). The previous equation has been simplified and adapted in many ways, as for instance, equation (3) presented below.

$$r_1 = r_{20}\theta^{(t-20)} \tag{3}$$

In this equation, r_1 is the rate constant at a temperate t, r_{20} is the rate at 20°C, and θ is a temperature coefficient.

For the direct application in microbial growth, many researches and reviews have been done. A work published by Noll et al (2020) presents a detailed history of the most important equations and methods. Under the gamma hypothesis, any of them could eventually be added to an integrated formula. For this work, we will focus in the Cardinal Model, presented in the next section.

3.2.2 Cardinal Model

The cardinal model considers 3 main parameters to evaluate the effects of the temperature on the growth kinetics of microorganisms. These are maximum temperature (T_{max}), minimum temperature (T_{min}) and optimal temperature (T_{opt}). Maximum and minimum temperatures stablish boundaries for the species development, setting the growth speed to 0 above or below the range. The optimal temperature indicates the temperature that will generate a maximum growth rate. This model was first introduced by Lobry et al (1991), and then further developed by the same authors and other collaborators in later works.

A main progress was made by Rosso et al (1993), as they presented the Cardinal Temperature Model with Inflection (CTMI). This model was built from empirical bases, showing high correlation with experimental measures. The prominent equation used is presented below.

$$\mu_{max} = \mu_{opt} \frac{(T - T_{max})(T - T_{min})^2}{(T_{opt} - T_{min})[(T_{opt} - T_{min})(T - T_{opt}) - (T_{opt} - T_{max})(T_{opt} + T_{min} - 2T)]} \tag{4}$$

Where μ_{opt} is the optimal growth rate (T^{-1}) at T_{opt}, and μ_{max} is the maximum growth (T^{-1}) rate at a temperature T. This formula has been used in this form in several studies, however, a more general expression exists formulated from the concept of the cardinal model, best suited for the gamma hypothesis, presented in equation (5):

$$\gamma(X) = \mu_{opt} \frac{(X - X_{max})(X - X_{min})^n}{(X_{opt} - X_{min})^{n-1}\left[(X_{opt} - X_{min})(X - X_{opt}) - (X_{opt} - X_{max})\left((n-1)X_{opt} + X_{min} - nX\right)\right]} \tag{5}$$

In this expression, $\gamma(X)$ is the gamma coefficient related to a X factor, which can be any of the multiple possible variables that can affect a species (temperature, pH, NaCl content, etc). The values *max*, *min* and *opt* are the equivalents for the factor X of the temperature related values described for equation (4). Finally, n is an adjust parameter than modifies the shape of the curve in order to improve the correlation with measured values. Typically, is a positive integer number. So, the cardinal model will be composed by 4 parameters, describing completely the influence of the factor X over a species. Notice that $\gamma(X_{opt}) = 1$, having for this value $\mu_{\max} = \mu_{\text{opt}}$.

3.2.3 Nutrients effect

The needs and response to different nutrients varies from each species. The classic approach for modeling this is based in the Monod's kinetic and several equations derived from it. The simplest form of the Monod's equation is presented here:

$$\mu = \mu_{opt} \frac{S}{K_s + S} \tag{6}$$

Where S is the concentration of a substrate, and K_s is the affinity constant for the substrate, or half-velocity constant. Notice that S is not a limitation in the media, then $\mu = \mu_{opt}$.

3.2.4 Other environmental factors

Based on the general expression for the cardinal model exposed previously, any factor can be modelled and added to a species characterization according to the gamma hypothesis, when four parameters are known.

The three parameters corresponding to the defining values of the factor are properties of each species. However, the adjust parameter n, is not clear if it depends on the species or the factor under analysis. For this reason, the literary review was expanded to search for values used in the study of various species in which the cardinal model was applied and to elaborate conclusions from this. The results are presented in chapter 4.

Some other environmental factors that could be added to the cardinal model in the construction of an impact index are the following ones:

- Turbidity: Turbidity, measured in NTU, has been studied in many opportunities how it may affect life forms (Hall and Thomas 2002). It is an indirect measure of the solids content of the water, and has direct relation with the amount of light and the depth it can penetrate through the water.
- Toxicity: There are many ways to measure or even to define the toxicity of a substance dissolved in the water. The Environmental Protection Agency (EPA) of the United States uses a methodology to estimate the LC50 and LD50, for a certain compound and a certain species (United States Environmental Protection Agency s.f.).
- COD: Chemical Oxygen Demand indicates the oxygen need to completely degrade the biodegradable compounds present in the water. As it will consume oxygen from the water and benefit the growth of some species over others, it may be considered to add to the model. It also may be useful to group several compounds whose degradation reactions are known, accounting all the oxygen needed and simplifying the final model, if the type of substances and concentrations are known.

3.3 Pollution

The causes of pollution that may modify the parameters of a habitat are as diverse as the human activities are. A natural mass of water may act as the final destination place for the discharge effluents of any industrial process, existing many possible factors acting together to affect life on it. In this section, the most important sources are covered, explaining and discussing their most relevant properties.

3.3.1 Types of pollution and sources

Some of the most relevant pollution sources are:

- Industrial wastewater: A large variety of quality and toxicity may be found in these effluents, depending the process where they were used. Normally the destination of the water is specified by legal norms which indicate the disposal and treatment, instead of a direct discharge to the environment. Municipal waste water plants normally are not designed to cope with many of the contaminants of these waters (emerging contaminants) beyond nutrients and organic matter, and must include advanced processes (Bolong, et al. 2009).
- Agricultural wastewater: Water used in the agriculture contains fertilizers, pesticides, and may pollute surface and groundwater. Major problems are non-point source pollution, which eventually leads to eutrophication of natural waters (Xia, et al. 2020). The management tries to optimize the quantities of used water, remaining a challenging task.
- Municipal sewage wastewater: This is the water generated by a city or a town. Normally it goes to a wastewater treatment plant where nutrients and COD are diminished to acceptable limits.
- Mining wastewater: As industrial wastewater, high toxicity of this effluent make is problematic to pour into a natural stream, and is not easy or cheap to treat it. Usually, pH is low due concentrations of sulfuric acid used in the refinement processes. In some mines, the water is stored or disposed with the tailings, and eventually evaporates, creating other scenarios. Cheap and new treatment techniques are in constant research (Iakovleva and Sillanpää, 2013).
- High salinity effluents: The brine of reverse osmosis plants enters in this category, but the sources are diverse, including mine discharges and the use of deicing agents (Szöcs, et al. 2014). A potentially growing issue, especially with the expected growing need of desalination plants in the future.
- High temperature effluents: Thermal power plants pour high temperature water back at the source where it was taken from. Cooling facilities are installed to contain the problem, but it is still a great altering factor in major rivers or natural water receiving the effluents of many plants (Raptis, Van Vliet and Pfister 2016).

- Radioactive effluents: Some manufacturing processes and investigations creates radioactive water, which cannot be poured into the environment and makes a highly costly managing problem.
- Oil spills: These are some of the major problems occurring at the ocean, heavily affecting sea life. However, leakages occur as well in facilities where oil or its derivates are stored, creating an issue specially for groundwater.
- Natural source: Natural causes may cause alterations to the normal state of a habitat. Volcanic emissions, floods, tidal waves and other phenomena may cause long term or permanent alterations of the environment.

4 Index Development

In this chapter, the development of the index from the information gathered in the previous section is described. The logic sequence starts with the characterization of the main parameters, and end ups with the proposal of impact categories depending on the values of the index.

4.1 Parameters characterization

A review of several studies was executed to determine values of the parameters of the cardinal model. The details of this review are presented in Annex 1.

The first task of the review was getting a defining value of *n*, the adjust parameter of equation (5). In the review, research was found on several species, where the extreme conditions in which they were put under to analyze their responses are presented in detail. Of all the studies verified for this information, most of them mainly analyze temperature, leaving pH, salt content and other factors in a second order of importance. Table 1 summarizes the most common values of *n* for three main factors found after the many reviewed studies: temperature, pH, and NaCl content.

Table 1: Summary of n adjusting values.

Factor	*n* value
Temperature	2
pH	1
NaCl content	1

Other values are used in some studies, but these are the most common and are considered representative. The difference between values anyway lies mainly in an improvement in the R^2 statistical correlation factor with the measured experimental values, but not in a significative difference in the equation curve. In the following sections it is indicated how these adjusting parameters were determined.

4.2 Temperature results

As mentioned before, temperature is the most studied environmental factor. In order to increase the validation of the previous parameters, the temperature values used for the model calibration in some of the studies are analyzed and commented. These are presented in Table 2.

Table 2: Temperature values for studied species

Species	Temperatures (°C)		
	T_{max}	T_{min}	T_{opt}
Aspergillus flavius	40	12.5	30.5
Brochothrix thermosphacta	30.85	-3.36	27.01
Clostridium perfringens	50.5	14.8	42.9
Lactococcus piscium	27.19	-4.8	23.39
Penicillium roqueforti	30.54	-12	23.8
Trichoderma harzianum	31.2	-0.8	25.5

- *Aspergillus flavius*: It is a kind of fungus that may parasite some animals. It is adapted to live in warm conditions, the reason it can't survive under 12°C.
- *Brochothrix thermosphacta*: This is one of most common bacteria that spoils meat and seafood stored in refrigerators. It is expected to have a temperature range where the max. temperature is not that high, and able to grow at low temperatures.
- *Clostridium perfringens*: It is a bacterium that may cause illness in humans due the toxins that liberates. It is common to find in food, being necessary to heat or re-heat it to above 50°C to kill the bacteria.
- *Lactococcus piscium*: It is a pathogen that affects some fish, like salmon or trout (fish from cold rivers). It is sometimes found in refrigerated food, being unable to survive high temperatures.

- *Penicillium roqueforti*: It is one of the fungi used in the production of different kinds of cheese. This process is usually made at low temperatures, being the fungi unable to adapt at higher temperatures.
- *Trichoderma harzianum*: It is a fungus presents in the majority of the soils, living in symbiosis at the roots of many plants. It is not adapted to high temperatures outside the soil.

Many of the reviewed species are different kinds of fungi. In these cases, the growth rate is not measured in T^{-1}. Instead the more conveniently adopted unit is LT^{-1}, specifically mm/h, where the magnitude being measure is the diameter or radius of a growing circle of fungi in the corresponding environment. The validation of the model under this condition open the possibility to the adaptation to other useful growing indicators, as for example sphere diameter or other medium physical property.

4.3 Index proposal

The proposal of an index of environmental impact is presented. The logical reasoning for it starts recalling from equation (1), where the gamma concept was presented. For a species s, the gamma of the specie will be the multiplication of all the gammas from every accounted factor that may affect the life of this species. This will be as follows:

$$\gamma_s = \prod_{i=1}^{r} \gamma_i(X_i) \tag{7}$$

Where r is the number of factors considered. From here, a generalization of the equation is presented. The values of $X_{i\text{-}max}$, $X_{i\text{-}min}$ and $X_{i\text{-}opt}$ for species s are the result of adaptation to the environment where it lives. Evidently, they will differ from one living form to another, but the average values of them may be represented by the values registered on their habitat. After all, if pollution occurs all life forms will be affected in some way, and the most general way to measure it is from the characteristics of the lake, pond, river or other natural water to which they belong. So, γ_s is renamed to γ_h, representing the gamma coefficient of the habitat affected by pollution, once all possible factors are considered.

This makes it necessary to have previously determined values for X_{opt}, X_{max} and X_{min}, which are easier to measure or assume.

The previous expression however, considers only the changes due to the water quality, so the next step is to add the effect of quantity changes.

The most general case to analyzed is when a water effluent comes from a source and is poured into a receiver mass. If the source is a natural body of water or stream, the environmental impact must consider both origin and the destination, this being the same when water is extracted for and industrial process and then returned to its origin with their qualities changed.

Below, Figure 1 and Figure 2 depict both described scenarios, where source and receiver are different and when they are the same.

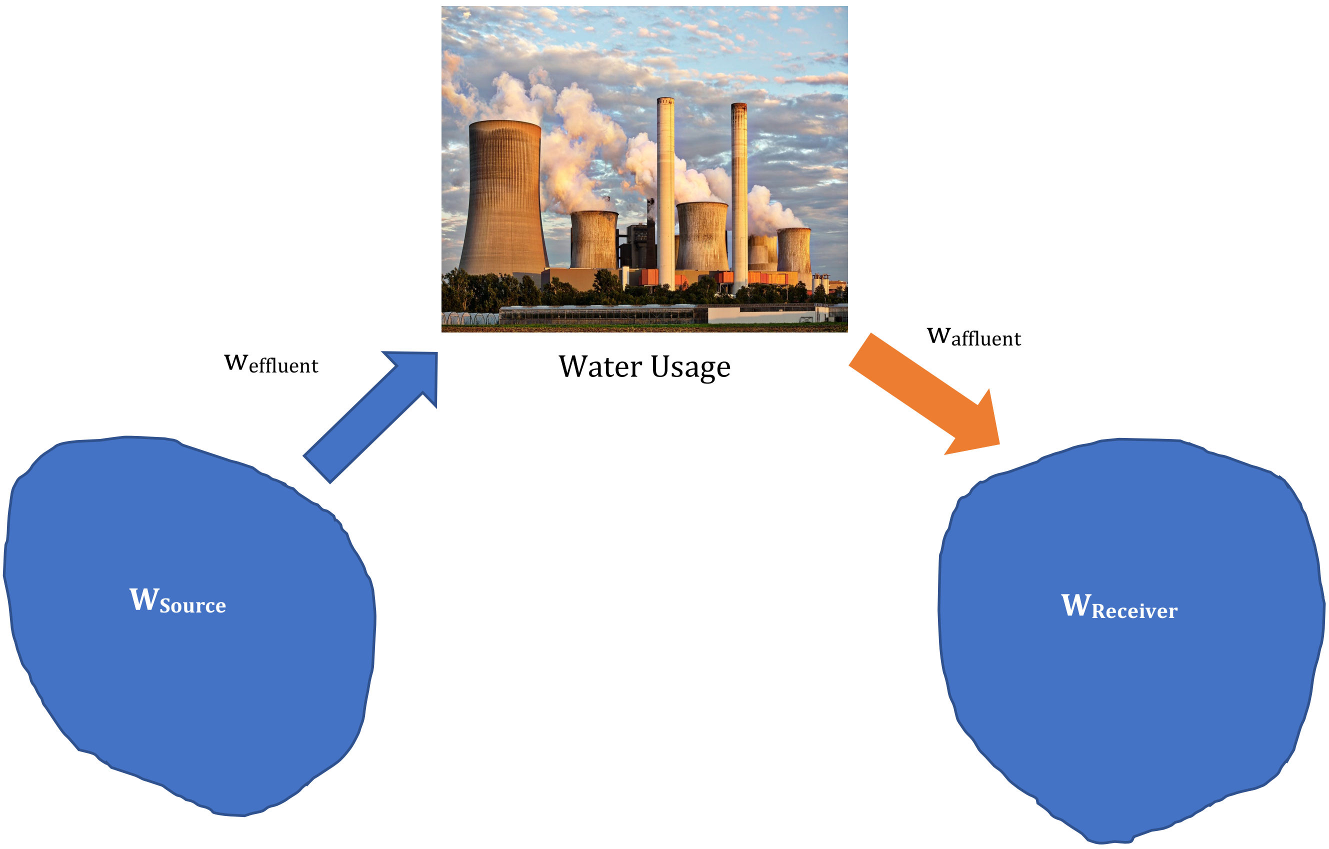

Figure 1: Example of situation where source and receiver are different

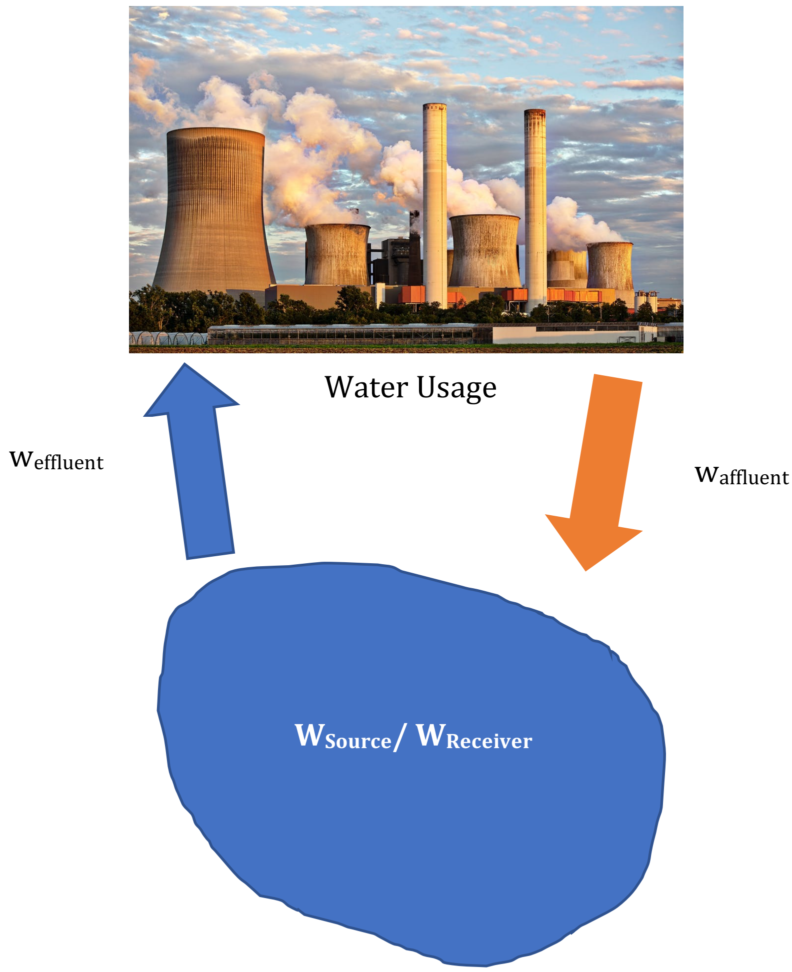

Figure 2: Example of situation where source and receiver are the same

In the previous figures, the terms are:

$W_{effluent}$: It is the flow of water being extracted from the source body. Depending on the characteristics of the case under study, it can be measured in volume units or flow units.

$W_{affluent}$: It is the flow of water being poured into the receiver body. Depending on the characteristics of the case under study, it can be measured in volume units or flow units.

$W_{receiver}$: It is the mass of water receiving the effluent, with certain quality characteristics. It can be measured in flow if it is a stream or in volume, otherwise.

W_{source}: It is the mass of water where the effluent is extracted from. It can be measured in flow if it is a stream or in volume, otherwise.

With this consideration, a primary proposal of the index is presented. It is basically a percental measure of the changes in quantity and quality, adjusted by the inclusion of the gamma values put together in equation (7).

$$EC_{\gamma h} = \frac{w_{effluent}}{w_{source}} + \frac{w_{affluent}}{w_{receiver}} \cdot \left(b + \frac{\left|\gamma_h(X_{aff}) - \gamma_h(X_{rec})\right|}{\gamma_h(X_{rec})} \right) \tag{8}$$

Where:

$\gamma_h(X_{aff})$: It is the gamma value evaluated for the qualities of the affluent.

$\gamma_h(X_{rec})$: It is the gamma value evaluated for the qualities of the receiver.

b: A coefficient that takes the value of 1 if source and receiver are different, and a value of -1 if source and receiver are the same.

The index is basically measuring the change in quantity and quality of both environments. The term of the left, $w_{effluent}/\ w_{source}$, indicates the mass change in the source. Logically the quality of the source doesn't change as a result. The term $w_{affluent}/\ w_{receiver}$ indicates the mass change in the receiver, multiplying the term for the quality change in this body. It adjusts the difference between the qualities of the 2 waters with an indirect mass balance, considering that the steady state of the mixture dynamics is already reached.

For the scenario where there is only the main mass of water, equation (8) is reduced to the expression below in equation (9).

$$EC_{\gamma h} = \frac{w_{effluent} - w_{affluent}}{w_{source}} + \frac{w_{affluent}}{w_{source}} \cdot \left(\frac{\left|\gamma_h(X_{aff}) - \gamma_h(X_{rec})\right|}{\gamma_h(X_{rec})} \right) \tag{9}$$

The term on the left is the direct consideration of the possibility of losses of water in the usage of it

4.4 Index properties

The first thing to note is that if the source and the receiver are the same and there are no changes in the quality and quantity of the flow, then $EC_{\gamma h} = 0$. This is an expected result, due the absence of any alteration in the environment. This can be obtained by a simple evaluation of equation (9).

If the qualities are the same, then the index will only account the impacts due to the addition or subtraction of mass, respectively.

The index is inversely proportional to the size of both source and receiver bodies of water. On the opposite, is directly proportional to the flows extracted or poured into them. These are other expected properties of the index.

More interesting is the behavior of the term related to the gamma coefficients. In its isolated form, it is part of the parenthesis:

$$\frac{\left|\gamma_h(X_{aff}) - \gamma_h(X_{rec})\right|}{\gamma_h(X_{rec})} \tag{10}$$

It is linear respecting to each coefficient, but as is presented in equations (5) and (7), it is non-linear respecting the physical variables which is representing. Each individual term has a range of values between 0 and 1, but since it is basically a percentage change respect to the receiver properties, it may eventually has a great value if the difference is higher than the base case. However, this is an extreme situation and very unlikely to happen. Even more extreme is if $\gamma_h(X_{rec}) = 0$, which basically means that no life is growing in the environment. These are non-real scenarios but it is mathematically possible to replace the equation with extreme low values of $\gamma_h(X_{rec})$ and obtain numerical results. In order to preserve the mathematical cohesion of the expression, it shall be restricted to $\gamma_h(X_{rec}) > 0.1$.

Once these values have been identified, it is clear that the Eco-gamma expression of equations (8) and (9) will most of times be lower than 1. To assist with future interpretation of the index, a weighting coefficient must be included. The value of this coefficient is highly related with the next section, which is the index categorization, but the final and most general form of the equation is presented below, where the weighting coefficient is represented as P.

$$EC_{\gamma h} = P\left[\frac{w_{effluent}}{w_{source}} + \frac{w_{affluent}}{w_{receiver}} \cdot \left(b + \frac{|\gamma_h(X_{aff}) - \gamma_h(X_{rec})|}{\gamma_h(X_{rec})}\right)\right] \tag{11}$$

Another property of the index is related to the precision and the number of variables integrated. From the gamma concept comes the fact that the way of adding variables is by multiplying their gamma coefficients. Since this is a number between 0 and 1, the more variables are added, the lower the resulting value of the gamma value will be. This however does not have as a direct consequence a higher or lower Eco-gamma index value, because the reduction is applied to both the affluent and the receiver, and the difference in the quantities must be accounted as well.

In the case of study of section 0, there is a situation where the adding of variables will decrease the value of the gamma coefficient of the receiver only, thus increasing the Eco-gamma index. If only mean values of the receiver parameters are available, it can be assumed that these values are equal to the optimum. In doing so, the gamma coefficient of the receiver will be 1, and then the quality part of the index will depend solely on the properties of the affluent. If the assumptions of the study lead to this situation, it should be indicated that the obtained index value is the minimum possible under this specific number of variables.

4.5 Categorization

It is necessary to assign impact categories to the possible values that the index can take. This is a standard procedure in constructing an index, such as the original Water Quality Index WQI (Horton, 1965), which evaluate the quality of a mass of water at certain point. In this case, the categories goes from very bad water quality to excellent water quality, representing a range of values between 0 and 100, and has been replicated with slight differences in later versions of the WQI.

To create the categories, the typical range of values of the Eco-gamma index must be identified first. It was mentioned that eventually equation (10) might not have upper limit. However, with the limit of $\gamma_h(X_{rec})$ established, its maximum value can be 9. It means a difference of 900% between the properties of the affluent and the receiver, in terms of gamma coefficients. This is an extreme situation, and due the properties of the index, the value of this term is expected to be less than 1 in most cases. In any case, it is a feasible situation and should be considered especially if the streams are important in size compared to the receiver.

The terms related to quantity change in theory don't have upper limit either. But it is extremely unlikely that any ratio would be greater than 1, meaning that the affluent flow is greater than the receiver. In fact, a volume difference of only 10% can be considered as very high, but there will always be exceptional cases. A notorious situation is the *water transfer* from one river to another. These major engineer projects cover the water needs of one region by extracting water from another basin, transporting it for up to several kilometers to its final destination. The largest example in existence today is the South-North Water Transfer Project in China, which has been developed to ensure the availability of water in Beijing. The scale of the project has many consequences and several studies about it has been carried out (Rogers, et al. 2020).

4.5.1 River/Lake separation

To better understand the scenarios, there may be 2 cases of source or receiver. They can be a static body of water, like a lake or lagoon; or any type of stream, for example a river or creek. For the evaluation of the index, which must be unitless, in the case of a static mass of water the effluent or affluent must be converted to an equivalent volume for a given period of time. This time can be chosen arbitrarily, and unless the total volume discharged into the receiver is being considered, it will only be an instantaneous measurement impact on the quality of the water, which will need additional monitoring and follow-up over time to see the evolution of its degradation.

In addition to the previous consideration, there is an important difference to be made regarding dispersion and flow mixing depending on where the affluent is discharged. If it is discharged into a stream, due the intrinsic movement of the water, the diffusion of the affluent will be complete at a certain point downstream. This may not occur when the discharge is made to a static body of water. This is important because this consideration can't be incorporated directly into the eco-gamma formulation, creating the need to adjust the value or the category for this scenario.

This distinction is made in the calculation of other indices. For example, in order to estimate the environmental damage with the goal of calculate a financial insurance, there exists the *Indice de Daño Medioambiental* (IDM). The calculation methodology (Boletin Oficial del Estado, 2015), considers not only the difference between these cases, but also includes categories according to the size of the receiver. It includes many other factors as well, which are not going to be included in this work, but that eventually can be added in the future (weather conditions or rainfall, for example).

The need of an adjustment between a static and a moving water is described in terms of the temporal evolution of quality on each one. However, depending on the natural affluents or discharges of the lake under analysis, additional considerations may be needed. Some lakes are of the endorheic type, which means that they have no natural discharge and the volume is balanced through infiltration and evaporation. With no natural evacuation, pollution can be a severe case due the difficulty of natural cleanse.

4.5.2 Proposal of Categories

With the previous discussion in mind, there are 4 major possible situations to consider:

a) Source and receiver are rivers
b) Source is a lake and receiver is a river
c) Source is a river and receiver is a lake
d) Source and receiver are lakes

These situations are sorted in what is initially a scale of less to more impact. If both are rivers, the impact is not expected to be as much as if both are lakes.

From equation (11) the weighting coefficient P was pending, and it was mentioned that it is related to the categorization of it. The ranges of values of the proposed categories depend on this parameter, which is merely an adjust to ease the reading and interpretation of the index and has no physical back-up. The proposed value for P will be 5000, and the resulting impact categories are shown in Table 3, where are crossed with the scenarios listed above.

Table 3: Proposed Categories

Eco-gamma value	Scenario a) and b)	Scenario c)	Scenario d)
0-10	Negligible Impact	Very low Impact	Low Impact
10-35	Very low Impact	Low Impact	Moderate Impact
35-50	Low Impact	Moderate Impact	High Impact
50-100	Moderate Impact	High Impact	Very High Impact
100-500	High Impact	Very High Impact	Extremely High Impact
500-1000	Very High Impact	Extremely High Impact	Extremely High Impact
> 1000	Extremely High Impact	Extremely High Impact	Extremely High Impact

The ranges are not equally divided basically because one of the main factors to influence the value of Eco-gamma is the ratio $w_{affluent}/ w_{receiver}$ and this is not linear. In fact, low values can mean a high impact, reason to set the first categories as linear and the highest impact ones on a logarithmic type scale. For scenarios a) and b), 8 different categories of environmental water quality impact are presented, going from Negligible to Extremely High. For the extra consideration of the cases where the receiver is a lake, the categories are upshifted in one numerical range, with the intention of increasing the impact denomination.

These categories allow a professional in charge of the respective study to have a first view of the problem and make quick decisions. Eventually more range of values can be added from future information, or the shift in the categories for scenarios c) and d) can be refined. Both cases may require additional information and will be a task for future work.

5 Application and case study

The Eco-gamma index approach was developed in a way to ease the evaluation in function of the parameters that are necessary for this. However, some of them may not be directly available for the evaluation.

In natural streams or water sources, for any parameter X, several measurements are needed to determine X_{min}, X_{max} and X_{opt}. This last one, can be assumed as the average value, with special attention if there is a recognizable seasonal cycle. From a good data sample, the average can be easily calculated, but uncertainty about the minimum and maximum may arise.

If the agent of pollution is coming from an industry or human activity, it is unlikely to exist reliable data about it, if any exists in the first place. Typically, companies are reluctant to share information if there is a possibility that they are releasing effluents with parameters over the limits stablished in the local regulation. In other cases, for example in water coming from irrigation fields, there can be no chance at all to exist any data, since most of the water infiltrates the soil to eventually get to an underwater body or emerge to a river.

A methodology to get all the necessary information should have to follow these steps:

1) Acquire all the already existing and available information from reliable sources.
2) Perform measurement campaigns, if it's possible.
3) Establish the missing values based on previous measurements, experience, literature or other sources.

In each of these steps it will be necessary to use criteria depending on the specific problem under analysis. In the next section, an example of application is presented and discussed, where different reasoning is used to overcome each lack of punctual information.

5.1 Application example

A quick application of Eco-gamma is the scenario of a thermal pollution in a river caused by the process of a thermal power plant. According to some studies (Langford 2001), the return temperatures of the water from a power plant reach up to 15 ^{O}C more than the temperature they are extracted from the source. This basic information allows to get results.

An example is the Widows Creek Power Plant, located in Alabama, United States. It was a carbon fueled plant, which currently is no longer in operation, waiting for investment to be converted into a renewable energy plant. It had 8 generating units and for its process it took water from the Tennessee River, just to be returned to same river. Relevant data of this plant and many others in the United States have been gathered and released by many publishers, and for this case data by the Union of Concerned Scientist was used (2011). Together, the 8 units took an average of 80.3 m^3/s from the river. The water was taken at 29.4 ^{O}C and returned at 36.1 ^{O}C. The mean flowrate of the Tennessee river is 1998 m^3/s.

No more information is available, so the next assumptions are made:

- No water losses are incurred in the process. Their addition to Eco-gamma is low in any case.
- Average temperature of the river will be considered as the optimal value. This way, $\gamma_h(X_{rec}) = 1$.
- Eventually, $\gamma_h(X_{rec})$ could be set as 0. This is assuming that a great disturbance is taken into the river. However, background information from Table 2 can be used. T_{max} is set to 50 °C and T_{min} to 0 °C, which is the freezing point. With these values, $\gamma_h(X_{rec})$ has a different value, which is closer to 1 rather than 0.

Table 4 shows a summary of the calculations resulting from the previous assumptions. The Eco-gamma value is 20.29, therefore, according to the categories of Table 3, is a very low impact. This can be interpreted as reasonable due the great difference existing when the discharge affluent and the flowrate of the river are compared. However, the calculation was made with the average flowrate, possibly changing if a notorious seasonal pattern exists.

Table 4: Summary of calculations – Application example

Affluent	$\gamma_h(X_{aff})$	0.899
Receiver	$\gamma_h(X_{rec})$	1
Global	$EC_{\gamma h}$	20.29

Another scenario possible is if the water is evaporated for a cooling tower instead of, instead of being heated directly. The total amount returned to the river would be much lower, entering the range of "negligible impact", which a is the desirable result.

5.2 Case of study – Ipojuca River, Brazil

An excellent case of study comes from the Ipojuca River, in the state of Pernambuco, Brazil. A research was conducted about the impacts that the sugar cane industry has on it (Gunkel, et al. 2007), which published many results including properties of river Ipojuca upstream and downstream the location of Usina Ipojuca, a major company that produces sugar and ethanol, whose activities have great impacts on the environment.

In the process of production there are several types of by-products that can be considered as waste. Of particular concern is the release of stillage, in a ratio of 156 liters per 1000 kg of sugar cane, obtaining 12 l of ethanol and 94 kg of sugar. This stillage is then mixed with irrigation water creating what is called "fertigation", from the words fertilizing and irrigation. The stillage retains many nutrients from the process, but its high organic load can be problematic and still cause contamination.

The main quality properties of the river and the fertigation fluid are presented below in Table 5 and

Table **6.** These parameters were measured during the dry season, in which the mean flow rate of the river is 2 m^3/s.

Table 5: Properties of Ijuca River near Usina Ipojuca

Parameter	Ipojuca River - Upstream		Ipojuca River - Downstream	
	Average	Standard deviation	Average	Standard deviation
Temperature °C	27.7	0.7	29.8	2.1
pH	6.7	0.4	6.3	0.5

Table 6: Properties of fertigation fluid

Parameter	Average
Temperature °C	36.8
pH	3.8

Despite the detailed information about the quality of the flows, there are no indications on their magnitude besides the average values of the Ijuca River for the dry and wet seasons: 2 m^3/s and 35 m^3/s, respectively. The reviewed study was focused on the global impact on the river rather than a specific mass balance, so this information was omitted from the final report if it existed in the first place. However, in the description of the process it is mentioned that the dilution ratio of the fertigation fluid is 6:4 for stillage to irrigation water.

To get an estimation of the stillage, there is public information about the production of Usina Ipojuca, available on its website (Ipojuca s.f. 2020). For the 2006/2007 season (year of publication of the study), the production was 716 246.74 tons of sugar cane. This means, that a total of $1.12x10^5$ m^3 of stillage was produced as a result. With the known ratio for irrigation water, a total of $1.87x10^5$ m^3 of fertigation fluid is obtained. It is unclear the rate of irrigation, though. According to some sources (Bundy Sugar s.f.), the sugar cane cultivation process may take between 12 and 16 months. Irrigation is supported by rainfall during the wet season, so for the matter of application, a time range of 6 months will be considered. This would mean a constant flow rate of fertigation fluid of 0.012 m^3/s.

For the Eco-gamma evaluation, as it was anticipated, the minimum and maximum values of the quality parameters are not clear. Only average values are provided with their standard deviation, which is not as considerable wide enough to set a range for the limits. If there is no more specific information, the data collected from the literary review and exposed in Table 2 can be used, as in the application example. T_{max} is set to 50 °C and T_{min} to 0 °C. For pH, the limits are 3 and 10.

The optimum value can be assumed as the mean value if no more data is available. Under this assumption, the Eco-gamma value of the natural water will be 1 (in this case is the receiver, Ipojuca River), but will provide a reasonable frame for the effluent evaluation.

Other important missing information is the source of water for the industrial activities. The most likely source is the Ipojuca river itself, but an important amount of water is collected from rainfall too. To simplify the problem, $w_{effluent}$ will be considered equal to 0, which has as a consequence that no impact for the water extraction is being accounted.

In Table 7 a summary of the input data for evaluation is found. Then in Table 8 the results of evaluation are presented.

Table 7: Input summary

Type of parameter	Parameter	Value
Global parameters	T_{max}	50 °C
	T_{min}	0 °C
	T_{opt}	27.7 °C
	pH_{max}	10
	pH_{min}	3
	pH_{opt}	7
Affluent parameters	*T affluent*	36.8
	$w_{affluent}$	0.012 m³/s
	pH affluent	3.8
Receiver parameters	$w_{receiver}$	2 m³/s

Table 8: Eco-gamma evaluation

Affluent	*$\gamma_h(X_{aff})$ - Temperature*	0.836
	$\gamma_h(X_{aff})$ - pH	0.326
	$\gamma_s = \prod \gamma_s(X_i)$	0.272
Receiver	*$\gamma_h(X_{rec})$ – Temperature*	1
	$\gamma_h(X_{rec})$ - pH	1
	$\gamma_s = \prod \gamma_s(X_i)$	1
Global	$EC_{\gamma h}$	51.84

The result of the Eco-gamma evaluation is 51.84, which falls in the category of Moderate Impact (Table 3). It fits well in the description of the environmental state described in the original publication, but some differences in accuracy should be noted. There are more quality parameters and other possible sources of contamination that can alter the Eco-gamma value, but as it is with this information at least establishes a basis for the index value and for the impact on water, knowing that an improvement in the precision and inclusion of more data will increase the value of Eco-gamma and will reflect the impact better.

5.3 Other possible applications

The previous case is a common case of pollution in a river, but this is one among many possible scenarios of pollution. In section 4.5.2, four scenarios were introduced, and there are others that can be adapted to fit in one these. A scenario of high interest for example is the discharge of any stream into the sea, being natural or manmade. The major problem here is how to define the receiver volume to make the evaluation possible. It will depend on each particular situation under study and their parameters. Due the complex hydrodynamics of a coast environment, if it's possible a numerical modelling of the area should be executed. Otherwise, assumptions of the average depth of the area and the use of satellite images may be useful to determine the influence of a stream, which will be easier depending on the type of pollutant and water color associated to it.

6 Conclusions

The development and application of Eco-gamma, a new environmental impact index for water quality degradation measure was made. However, there are many aspects of it that have room for improvement, refinement, or expansion of their applications.

From the gamma concept and the inclusion of more variables, improvement can be made in the evaluation of the base parameters, for example, the adjustment parameter *n*. In regards of the optimal, maximum and minimum values of the variables, a more complete data set can refine the accuracy of them, and thus provide a better back up information if these values are missing in an ongoing study. If it is possible, it should be supported by field information, rather than laboratory experiments. As it was mentioned in chapter 3, the variables behind the inhibition or growing of any species are basically the same, but it would improve the supporting thesis of this work if is based on direct field measurements.

Since the evaluation of the Eco-gamma index may depend on the number of variables included, this number should be explicitly indicated for each application. An interesting case study is the analysis of how the value of the index would vary in each combination of all the available variables, to see if it is possible to include a correction parameter in the Eco-gamma equation below without the need to separately indicate the number of variables.

$$EC_{\gamma h} = \frac{w_{effluent}}{w_{source}} + \frac{w_{affluent}}{w_{receiver}} \cdot \left(b + \frac{\left| \gamma_h(X_{aff}) - \gamma_h(X_{rec}) \right|}{\gamma_h(X_{rec})} \right)$$

6.1 Future tasks

In a similar line, a future task will be the analysis of inclusion of external variables in the Eco-gamma formulation. Only water-related parameters are used on this work, but eventually rainfall, humidity, solar radiation and other factors could be added. Whether it can be added to the same equation or additional terms need to be included is unclear today.

Another aspect that can be improved as more times the Eco-gamma index is used is the number of categories and the adjust parameter P of equation (11). The number of categories and their upper and lower limits were defined based in previous indices such as WQI and including the fact that the difference in quantities of the affluent respect to the source or receiver will dominate the magnitude of the index starting at lower values of their respective ratios, due to its non-linearity. As more cases are analyzed, it could be possible to perform a more accurate calibration of the categories when they are compared to the real impact found in the water. It may be also possible to identify if a deeper separation of scenarios (static-moving waters) is needed.

6.2 Closure

As a new index, Eco-gamma could have many applications. It is necessary to remind that this is an index that tries to account both the alteration in the quality and quantity of the water due its usage. It is not the idea to measure the punctual quality of the water, but rather how impactful is an activity compared to a reference level. This reference level may be the optimal for some species and harmful to other ones or vice versa, and this is the reason that talking about a punctual quality could be unclear. This is not a usual way to assess the impact of human activities on the environment, but it should be a growing trend. As stress over the natural resources continues to grow, bordering water scarcity in many regions, special care must be taken on a responsible use. The impacts due human activity, which will continue to exist, must reflect as best as possible what is really happening in order to take measures to prevent, correct the activity or even decree legal and financial sanctions. This way, Eco-gamma could be used as a tool for water and environmental management, providing a new approach to solving problems with physical, economic and social impacts.

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8 Annexes

Annex 1

Table 9: Main properties of selected species from the literary review

Species	Parameters																
	u_{opt} (1/h)	T				pH				NaCl				Water Activity			
		T_{min}	T_{max}	T_{opt}	n	pH_{min}	pH_{max}	pH_{opt}	n	$NaCl_{min}$	$NaCl_{max}$	$NaCl_{opt}$	n	aw_{min}	aw_{max}	aw_{opt}	n
Annamox	0.29	10	40	31	2												
Aspergillus carbonarius (2 straina)	0.33125	0.08	40.54	34.2	2									0.826	0.999	0.962	2
Aspergillus flavus	19.96 mm/day	8.24	40.2	33.6	2												2
Aspergillus flavus	1.6	12.5	40	30.5										0.794	1	0.958	
Aspergillus fumigatus	2.47	10.8	45	37.3										0.836	1	0.975	
Aspergillus niger		11	47.5	31.8	2												
Aspergillus niger (on citrus solution)	variable	14.74	31.45	40.08	2												
B. thermosphacta	0.64	-3.36	30.85	27.01	2	4.79		7.11	1		62.24 g/l	0	1				
BACTERIAS ANAEROBICAS GENERICAS		5	40	30	2												
Clostridium perfringens	5.25	14.8	50.5	42.9	2												
Clostridium perfringens (Oxyrase)	5.2	15.4	51.1	46.7	2?												
Emericella nidulans		8.9	47	35.4	2												
Escherichia coli K12	2.52	9.23	35.46	45.77	2	3.95	9.71	6.16	1								
Escherichia coli K12 MG1655	2.3					4.3	9.89	7.61	1								
Escherichia coli O157:H7 (on Lettuce)	1.41	8.21	45	37	2									0.8	1	0.98	
Escherichia coli O26	4.27	6.81	45.16	40.97	2	4	8.98	6.49	1					0.941	1	0.998	2
Hyphopichia burtonii (Sabouraud medium at 30º)	1.25 mm/day					1.87	10.4	4.94									
L. piscium CNCM I-4031	0.75	-4.8	27.19	23.39	2	4.79		7.36	1		23 g/l	4.69 g/l	1				
Mucor brunneogriseus		-5.2	25.8	21.4	2	3.2	6.58	8.78	1								
Mucor circinelloides		-1.2	40.9	29.2	2	2.89	6.49	8.52	1								
Mucor endophyticus		0.2	37.1	26.3	2	2.74	5.37	9.66	1								
Mucor fuscus		2.3	32.1	25.1	2	3.16	5.01	9.87	1								
Mucor lanceolatus		-2.4	33.6	24.5	2	3.02	4.92	10.92	1								
Mucor racemosus		-5.7	33.7	25.7	2	3.09	5.01	9.64	1								
Mucor spinosus		-2.7	37.2	27	2	2.39	4.97	9.71	1								
Paecilomyces variotii		5.9	40.3	32.1	2												
Penicillium brevicompactum (sorbic acid solution at 2000 mg/l)	0.198					4.7	5.3	5	1								
Penicillium camemberti		-1.4	33.5	26.9	2	2.91	14	5.52	2					0.83	1	0.99	2
Penicillium roqueforti		-12	30.54	23.8	2												
Penicillium roqueforti		-0.2	33.6	26.9	2	2.84	13.8	5.68	2					0.83	1	0.99	2
Penicillium sp.	0.71	12	37.3	25.8	2?									0.75	1	0.954	2?
Pichia anomala (Sabouraud medium at 30º)	0.327 mm/day					0.719	11.3	4.34									
Pichia kluyveri	0.73	-9.2	45	37.6	2	2.4	9	4.3	0.1								
Saccharomycopsis fibuligera (Sabouraud medium at 30º)	0.732 mm/day					2.07	4.61	11.5									
Salmonella enterica serovar Typhimurium ADQP 305		5.06	46.48	39.3	2	3.58	10.42	7	1					0.951	1	0.997	1
Trichoderma harzianum		-0.8	31.2	25.5	2												

Table 10: References and additional information of the selected species from the literary review

Species	Reference	Additional information about the species
Annamox	Kinetic implication of moving warm side-stream Anaerobic ammonium oxidizing bacteria to cold mainstream wastewater	
Aspergillus carbonarius (2 straina)	Modelling the effect of temperature and water activity on the growth of two ochratoxigenic strains of Aspergillus carbonarius from Greek wine grapes	https://www-sciencedirect-com.sire.ub.edu/topics/agricultural-and-biological-sciences/aspergillus-carbonarius
Aspergillus flavus	Modelling the effect of temperature and water activity of Aspergillus flavus isolates from corn	https://web.archive.org/web/20130609082232/http://www.aspergillusflavus.org/aflavus/index.html
Aspergillus flavus	Using the gamma concept in modelling fungal growth: A case study on brioche-type products	https://web.archive.org/web/20130609082232/http://www.aspergillusflavus.org/aflavus/index.html
Aspergillus fumigatus	Using the gamma concept in modelling fungal growth: A case study on brioche-type products	https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3857757/
Aspergillus niger	A Model for the Combined Effects of Temperature and Salt Concentration on Growth Rate of Food Spoilage Molds	https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/aspergillus-niger
Aspergillus niger (on citrus solution)	Growth Modeling of Aspergillus niger Strains Isolated from Citrus Fruit as a Function of Temperature on a Synthetic Medium from Lime (Citrus latifolia T.) Pericarp	https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/aspergillus-niger
B. thermosphacta	Influence of temperature, pH and NaCl concentration on the maximal growth rate of Brochothrix thermosphacta and a bioprotective bacteria Lactococcus piscium CNCM I-4031	https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/brochothrix
BACTERIAS ANAEROBICAS GENERICAS	Risk index to monitor an anaerobic digester using a dynamic model based on dilution rate, temperature, and pH	
Clostridium perfringens	Growth of Clostridium perfringens in cooked chicken during cooling: One-step dynamic inverse analysis, sensitivity analysis, and Markov Chain Monte Carlo simulation	https://food.unl.edu/clostridium-perfringens
Clostridium perfringens (Oxyrase)	Effect of combination of Oxyrase and sodium thioglycolate on growth of Clostridium perfringens from spores under aerobic incubation	https://food.unl.edu/clostridium-perfringens
Emericella nidulans	A Model for the Combined Effects of Temperature and Salt Concentration on Growth Rate of Food Spoilage Molds	https://www.sciencedirect.com/topics/biochemistry-genetics-and-molecular-biology/emericella
Escherichia coli K12	Impact of pH on the cardinal temperatures of E. coli K12: Evaluation of the gamma hypothesis	
Escherichia coli K12 MG1655	Mechanistic modelling of the inhibitory effect of pH on microbial growth	
Escherichia coli O157:H7 (on Lettuce)	Modeling the Combined Effect of Temperature and Relative Humidity on Escherichia coli O157:H7 on Lettuce	
Escherichia coli O26	Development and Validation of Experimental Protocols for Use of Cardinal Models for Prediction of Microorganism Growth in Food Products	
Hyphopichia burtonii (Sabouraud medium at 30º)	A model for the effect of pH on the growth of chalk yeasts	https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/hyphopichia
L. piscium CNCM I-4031	Influence of temperature, pH and NaCl concentration on the maximal growth rate of Brochothrix thermosphacta and a bioprotective bacteria Lactococcus piscium CNCM I-4031	https://sfamjournals.onlinelibrary.wiley.com/doi/full/10.1111/jam.13179
Mucor brunneogriseus	Effect of temperature, pH, and water activity on Mucor spp. growth on synthetic medium, cheese analog and cheese	http://www.bioref.lastdragon.org/Mucoromycotina/Mucor_brunneogriseus.html
Mucor circinelloides	Effect of temperature, pH, and water activity on Mucor spp. growth on synthetic medium, cheese analog and cheese	https://www.sciencedirect.com/topics/biochemistry-genetics-and-molecular-biology/mucor-circinelloides
Mucor endophyticus	Effect of temperature, pH, and water activity on Mucor spp. growth on synthetic medium, cheese analog and cheese	
Mucor fuscus	Effect of temperature, pH, and water activity on Mucor spp. growth on synthetic medium, cheese analog and cheese	
Mucor lanceolatus	Effect of temperature, pH, and water activity on Mucor spp. growth on synthetic medium, cheese analog and cheese	https://www.npr.org/sections/thesalt/2018/01/29/579747917/the-cheese-does-not-stand-alone-how-fungi-and-bacteria-team-up-for-a-tastier-rin?t=1584917520361
Mucor racemosus	Effect of temperature, pH, and water activity on Mucor spp. growth on synthetic medium, cheese analog and cheese	https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/mucor-racemosus
Mucor spinosus	Effect of temperature, pH, and water activity on Mucor spp. growth on synthetic medium, cheese analog and cheese	
Paecilomyces variotii	A Model for the Combined Effects of Temperature and Salt Concentration on Growth Rate of Food Spoilage Molds	https://drfungus.org/knowledge-base/paecilomyces-species/
Penicillium brevicompactum (sorbic acid solution at 2000 mg/l)	Growth rate and growth^no-growth interface of Penicillium brevicompactumas functions of pH and preservative acids	https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/penicillium-brevicompactum
Penicillium camemberti	Modelling the effect of temperature, pH, water activity, and organic acids on the germination time of Penicillium camemberti and Penicillium roqueforti conidia	https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/penicillium-camemberti
Penicillium roqueforti	A Model for the Combined Effects of Temperature and Salt Concentration on Growth Rate of Food Spoilage Molds	https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/penicillium-roqueforti
Penicillium roqueforti	Modelling the effect of temperature, pH, water activity, and organic acids on the germination time of Penicillium camemberti and Penicillium roqueforti conidia	https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/penicillium-roqueforti
Penicillium sp.	Using the gamma concept in modelling fungal growth: A case study on brioche-type products	https://drfungus.org/knowledge-base/penicillium-species/
Pichia anomala (Sabouraud medium at 30º)	A model for the effect of pH on the growth of chalk yeasts	https://www.ncbi.nlm.nih.gov/pubmed/16423066
Pichia kluyveri	Modeling mixed fermentation of gowé using selected Lactobacillus plantarum and Pichia kluyveri strains	https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/pichia-kluyveri
Saccharomycopsis fibuligera (Sabouraud medium at 30º)	A model for the effect of pH on the growth of chalk yeasts	
Salmonella enterica serovar Typhimurium ADQP 305	Extending the gamma concept to non-thermal inactivation: A dynamic model to predict the fate of Salmonella during the dried sausages process	https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3623383/
Trichoderma harzianum	A Model for the Combined Effects of Temperature and Salt Concentration on Growth Rate of Food Spoilage Molds	https://www.jstor.org/stable/42939228?seq=1