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Quantification of Environmental Reactive Oxygen Species (ROS) by Chromo-Stoichiometry: Development and Validation of the Monagas Variant

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Abstract**—** *This research develops a quantitative model for estimating reactive oxygen species (ROS) in ambient air using a chromo-stoichiometric approach applied to the traditional Schönbein scale. Starting from the stoichiometric relationship between ozone (*O_3*) and water vapor as precursors of hydroxyl radicals (OH·), and considering ozone as the limiting reagent, a direct conversion is established between the Schönbein number and the OH· emission rate expressed in* $mol{\cdot}cm^{-3}{\cdot}s^{-1}$*. This transformation results in the so-called "Monagas Variant," which converts a qualitative tool based on the colorimetric change of potassium iodide reagent strips into a quantitative method for radical estimation.*

The model integrates the conversion of ozone concentrations (ppb) to amount of substance, the calculation of absolute humidity, and the application of stoichiometric relationships to determine the theoretical production of OH· during a standard 8-hour exposure period. The results allow for the classification of ambient oxidation into three levels (LOW, MIDDLE, and HIGH), defined by ranges of radical emission. Experimental validation, performed in a 1 m^3 *tank with an Open Air Factor (OAF) generator and through comparative tests with 17.5% hydrogen peroxide, showed consistent agreement between the observed color change and the values calculated by the model.*

The data obtained, on the order of 10^6*–*10^7 $mol{\cdot}cm^{-3}{\cdot}s^{-1}$*, are consistent with values reported in the literature on ozone photolysis at air-water interfaces and atmospheric OH· production. Furthermore, it is shown that reliable determinations can be made in just 90 minutes, significantly reducing the evaluation time compared to the full 8-hour cycle. The Monagas Variant thus constitutes an accessible, reproducible, and low-cost tool for monitoring environmental oxidative capacity and assessing OAF in indoor spaces, offering a practical solution for the rapid control of advanced oxidation processes and indoor air quality.*

Keywords— Hydroxyl radicals (OH·), Reactive oxygen species (ROS), Monagas Variant, Schönbein scale, Open Air Factor (OAF), Chromo-stoichiometry, Indoor Air Quality (IAQ), Advanced Oxidation Processes (AOPs), Atmospheric environmental chemistry.

I. INTRODUCTION

1.1 Current Situation and Reason for the Study:

The recent COVID-19 pandemic has highlighted and accelerated, in just over three years, a large number of new trends, behaviors, regulations, and requirements surrounding indoor disinfection. The need to meet these disinfection requirements in public places, such as supermarkets, businesses, hospitals, and hotels, to maintain a pathogen-free environment as much as possible, has led to the reappearance and uncontrolled use of a multitude of existing products and substances, as well as new ones, mostly oxidizers. Some of these are already part of our daily lives, such as bleach, alcohols, peroxides, chlorinated compounds, ozone, etc.

Therefore, it is increasingly necessary to be able to quantify the role of oxidants in indoor environments, both for the air and for the surfaces where they are applied, since they all have a direct and indirect relationship with health: direct through dispersion in the environment through breathing and contact with these substances, and indirect through evaporation or methods of application that can end up in food and all kinds of consumer products.

TABLE 1
PERMISSIBLE EXPOSURE LIMITS FOR OZONE AND HYDROGEN PEROXIDE

Agency	Ozone (O_3)	Hydrogen Peroxide (H_2O_2)	Regulatory Context
WHO	100 µg/m³ (~0.05 ppm)	No specific ambient air limit	8-hour daily average. WHO Global Air Quality Guidelines (2021)
OSHA	0.1 ppm (0.2 mg/m³)	1 ppm (1.4 mg/m³)	Permissible Exposure Limit (PEL) - 8-hour TWA. 29 CFR 1910.1000
FDA	0.05 ppm	GRAS (Generally Recognized as Safe)	Max. for medical devices in occupied spaces / Food additive safety

Source: Own elaboration

The Open Air Factor (OAF) is well-known in nature and has an environmental sanitizing effect. In Garcia Raurich et al. (2023), it was theoretically demonstrated that, artificially, with the appropriate proportion and combination of reactants, it is possible to achieve, in indoor environments, the same level of hydroxyl radical molecules generated as in nature, using only two reactants: hydrogen peroxide and almost negligible amounts of ozone, without ever exceeding the maximum recommended emission levels established by WHO, OSHA, and FDA.

The immediate, involuntary, and vital need to breathe and move about in a safe, sanitized environment makes it practically impossible to quickly and easily determine whether these required safety parameters are being met. Therefore, the need arises to be able to detect the presence of oxidants in a given environment in near real-time, without sophisticated laboratory equipment.

1.2 Reactive Oxygen Species (ROS):

Reactive oxygen species (ROS) refer to a group of reactive molecules and free radicals derived from molecular oxygen (O_2). Recent work (Held, P., 2015) demonstrates that ROS are responsible for activating cell signaling cascades, in addition to serving as cellular messengers. Most ROS are produced as byproducts of mitochondrial electron transport, such as the reactions that occur during the reduction of atomic oxygen. In fact, because atomic oxygen has two unpaired electrons in separate orbits, its structure is susceptible to radical formation.

The effect of ROS on cellular processes, oxidative stress, depends on the concentration, duration, and context of exposure. The typical cellular response to stress is the detoxification of reactive intermediates to repair the corresponding damage. Peroxides and free radicals that emerge from molecular oxygen can cause toxic effects on all components of the cell. However, it has been shown that some ROS, such as hydroxyl radicals ($OH\cdot$), have a short half-life of $\sim 10^{-9}$ s, thus inhibiting this effect in humans, animals, and plants.

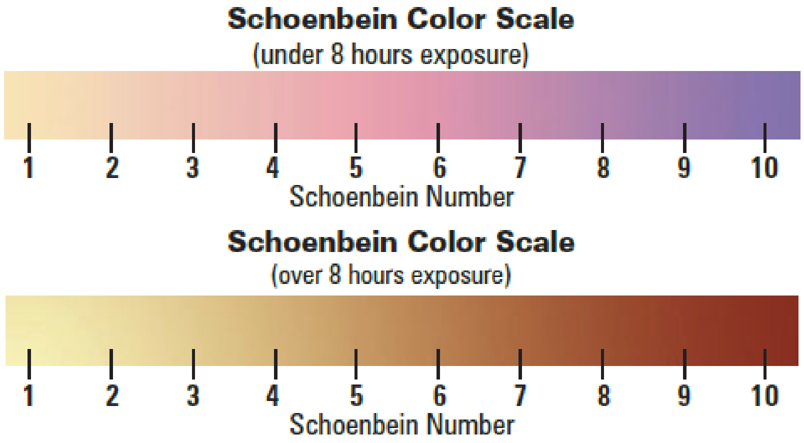
Furthermore, these ROS are always present in the natural environment. Therefore, it is evident that these ROS could be measured by monitoring oxidation processes in the air. In a first approach, presented in Garcia Raurich et al. (2023), an estimate of ROS concentration can be correlated by monitoring $OH\cdot$, as they have the second highest oxidation potential. However, a complete correlation between the $OH\cdot$ concentration and the absolute ROS concentration will never be achieved.

One of the most common processes that produces hydroxyl radicals is the reaction between hydrogen peroxide and ozone, both in the gas phase. The maximum reaction efficiency is achieved with the stoichiometric ratio of the reactants. Therefore, the maximum oxidative efficiency also corresponds to the maximum concentration of $OH\cdot$ and the minimization of waste, which is achieved at different ambient volumes depending on the purity of the hydrogen peroxide and considering an initial ozone concentration of 0.05 ppm. Specifically, the volume required to obtain maximum efficiency increases with the purity of the peroxide. In any case, an OH· emission of $\sim 4.4 \times 10^7\ \mathrm{mol \cdot cm^{-3} \cdot s^{-1}}$ is obtained, consistent with experimental results obtained in other studies (Anglada et al., 2014).

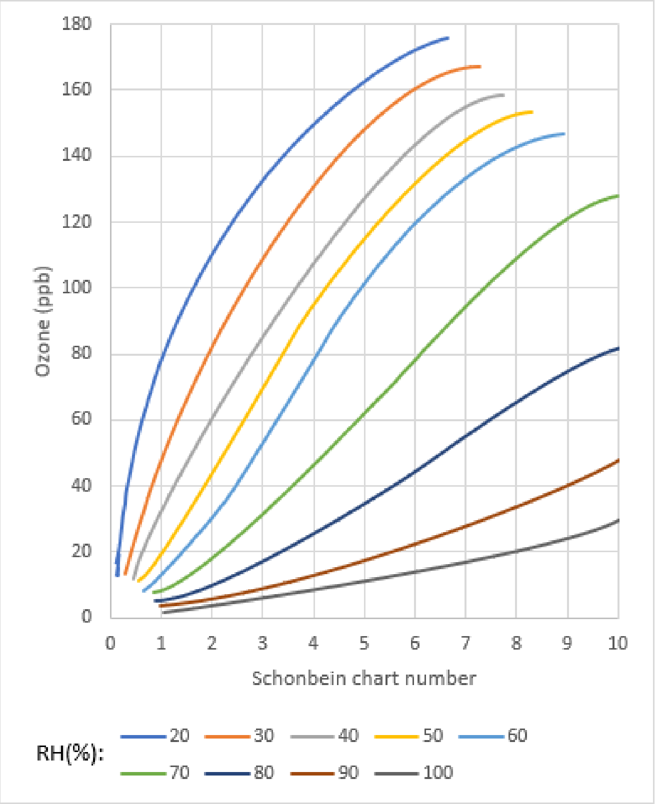
$$O_3 + H_2O_2 \longrightarrow OH\cdot + O_2 + O_2H\cdot \qquad \textbf{(R1)}$$

The quickest and simplest qualitative methods available, used in a wide variety of studies, including those conducted at environmental monitoring stations and in academic settings, employ the Schönbein reagent strip to analyze ambient ozone present in nature (UCAR, [online]). The reaction between potassium iodide (KI), ozone (O_3), and water (H_2O) produces corresponding color scales, which represent different ozone concentrations under varying relative humidity.

$$2KI + O_3 + H_2O \longrightarrow 2KOH + O_2 + I_2 \qquad \textbf{(R2)}$$



GRAPHIC 1: Schönbein chart values for colors. Workman and Frye (JoVE Journal, Science Education Collection, Measuring Tropospheric Ozone)



GRAPHIC 2: Schönbein chart for different ambient humidity values. Several Departments of Environmental Quality employ this Schönbein chart to measure ozone concentration in air. Workman and Frye (JoVE Journal, Science Education Collection, Measuring Tropospheric Ozone)

Given a specific relative humidity (RH) value, as the concentration of ozone in the air increases, the Schönbein number also increases, implying a decrease in color brightness. Furthermore, as the presence of water vapor in the air (relative humidity) increases, the ozone concentration corresponding to a given color decreases. Thus, due to the presence of ozone and moisture in the air, the well-known Schönbein number table also demonstrates that the scales represented are influenced by the presence of oxidizing reactive oxygen species (ROS), such as hydroxyl radicals (OH·).

$$2O_3 + H_2O \longrightarrow 2OH\cdot + 2O_2 + O_2H\cdot \qquad \textbf{(R3)}$$

Given that other oxidants besides ozone and molecular oxygen exist in nature, such as the hydroxyl radical (OH·), produced by ozone photolysis as the main source of these radicals (Stone et al., 2012; Carslaw et al., 2017), it seems logical to consider measuring this oxidizing molecule, considered the most important "cleaner" of the troposphere (George, C. et al., 2015; Ruiz-Lopez et al., 2020). It is called the "detergent of the atmosphere" due to its high reactivity, and despite this high reactivity, it remains at appreciable concentrations because it is regenerated in several of the chain processes in which it participates.

Therefore, by taking advantage of the Schönbein color chart and carefully analyzing the ozone concentration values that make up this internationally accepted color scale and the ozone chart for different relative humidity levels, the corresponding hydroxyl radical emission is obtained by calculating the required stoichiometry. This reveals the amount of OH· associated with each color shown on each scale and allows for the creation of another variant of the same chart and scale, this time to determine the number of OH· molecules needed for that equivalent oxidation.

II. THEORETICAL DERIVATION OF THE MONAGAS VARIANT

2.1 Conversion of Ozone Concentration to Amount of Substance:

The first step is to express each reactant data point as the amount of substance in moles. Ozone concentration information is expressed in parts per billion (ppb). Consequently, the amount of substance is calculated considering the molar volume under standard conditions for an ideal gas (1 atm of ambient pressure, which is 22.4 L/mol). The required conversion is shown below:

$$ppb_{O_3}[ppb].\frac{1\left[\frac{L_{O_3}}{L}\right]}{10^9[ppb]}.\frac{1\ mol_{O_3}}{22.4\ L_{O_3}} = 4.464.ppb_{O_3}.10^{-11}.\left[\frac{mol\ O_3}{L}\right] \qquad \textbf{(R4)}$$

2.2 Calculation of Absolute Humidity:

On the other hand, the absolute amount of water in the reaction can be obtained from the Relative Humidity (RH) values in %. This value is due to the ratio between the water vapor pressure in the air and the corresponding vapor pressure under saturation conditions. Relative humidity should never be understood as the ratio of the volume of water to the volume of air, or anything similar. Therefore, the Absolute Humidity (AH), which is the actual ratio of the mass of water to the volume of air in kg/m³, can be obtained using the following expressions:

$$AH = \frac{m_w}{V} = \frac{e_w\cdot(RH/100)}{R_vT} \qquad \textbf{(R5)}$$

Where $R_v = 461.5\frac{J}{kg\cdot K}$ is the gas constant for water vapor, T is the ambient temperature in Kelvin, and e_w is the saturation pressure of water vapor in Pascals, which is calculated as follows:

$$e_w(p,t) = (1.0016 + 3.15\cdot 10^{-6}p - 0.074\cdot p^{-1})\cdot 6.112\cdot exp\ exp\ \left(\frac{17.62t}{243.12+t}\right) \qquad \textbf{(R6)}$$

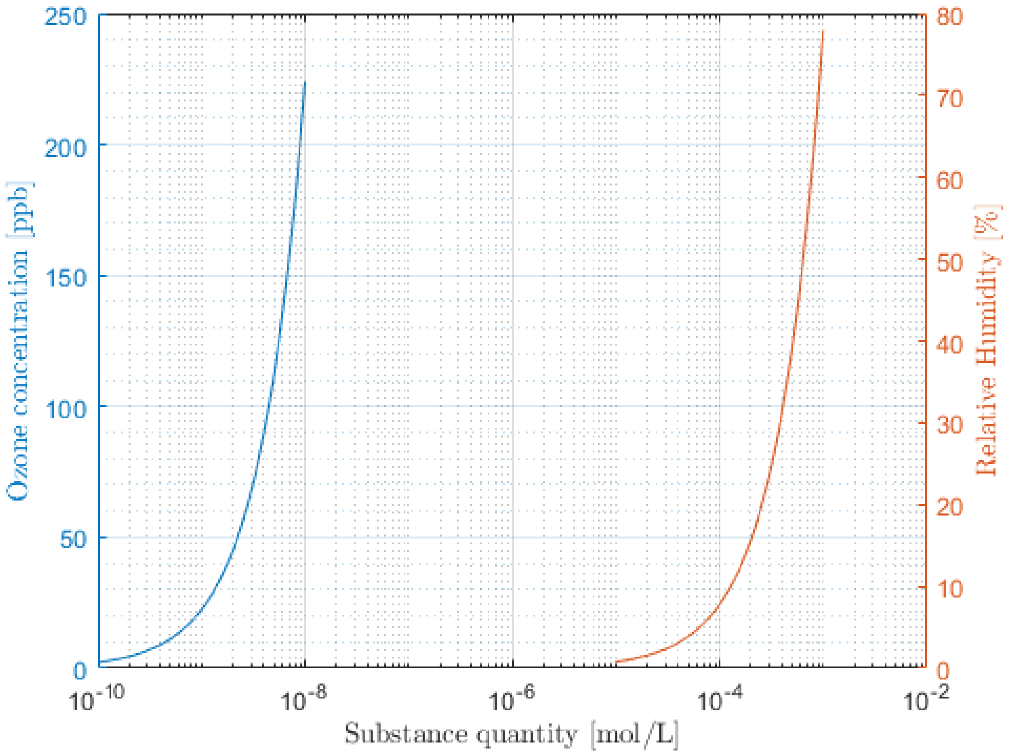
Where p is the ambient pressure in hPa and t is the ambient temperature in °C. The value of e_w obtained with this last equation is expressed in hPa, so the value used in the Absolute Humidity equation will first be converted to Pa.

Finally, the amount of water substance per unit volume is obtained as follows:

$$AH\ \left[\frac{kg}{m^3}\right]\cdot\frac{1000\,g}{1\,kg}\cdot\frac{1\,m^3}{1000\,L}\cdot\frac{1\,mol\,H_2O}{18\,g} = \frac{AH}{18}\ \left[\frac{mol\,H_2O}{L}\right] \qquad \textbf{(R7)}$$

2.3 Identification of the Limiting Reactant:

At this point, the next step is to identify which of the reactants is the limiting one. Therefore, a range of values for both ozone concentration and relative humidity is compared in terms of the amount of the related substance.



GRAPHIC 3: Comparison of ozone concentration with relative air humidity in terms of the amount of related substance (Own elaboration)

It can be observed that, in any case, the amount of ozone participating in the reaction is between four and five orders of magnitude lower than the corresponding amount of water vapor. Therefore, it is concluded that ozone is always the limiting reactant, again justifying the direct correspondence between the Schönbein color scale defined by ozone and the emission of hydroxyl radicals, which are directly related to the luminosity of that color.

2.4 Calculation of Hydroxyl Radical Generation:

Once ozone is identified as the limiting reactant, the amount of OH· generated from the reaction of ozone with water vapor is calculated as shown below:

$$n_{OH\cdot} = 4.464 \cdot ppb_{O_3} \cdot 10^{-11} \left[\frac{mol\ O_3}{L}\right] \cdot \frac{2\ mol\ OH\cdot}{2\ mol\ O_3} = 4.464 \cdot ppb_{O_3} \cdot 10^{-11} \left[\frac{mol\ OH\cdot}{L}\right] \quad \textbf{(R8)}$$

$$molec_{OH\cdot} = n_{OH\cdot} \left[\frac{mol\ OH\cdot}{L}\right] \cdot \frac{6{,}022 \cdot 10^{23}\ molec\ OH\cdot}{1\ mol\ OH\cdot} = 26.8822 ppb_{O_3} 10^{12} \left[\frac{molec\ OH\cdot}{L}\right] \quad \textbf{(R9)}$$

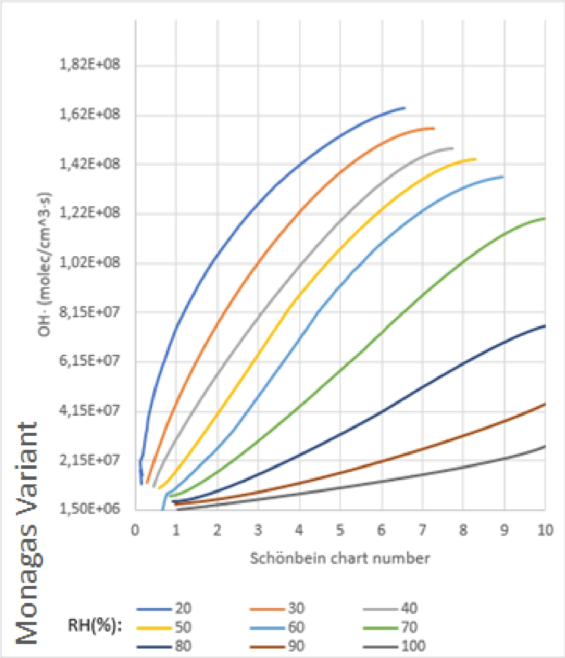
$$molec_{OH\cdot} = 26.8822 ppb_{O_3} 10^{9} \left[\frac{molec\ OH\cdot}{cm^3}\right] \quad \textbf{(R10)}$$

2.5 Calculation of OH· Emission Rate:

Finally, the OH· emission rate is obtained by dividing the previous expression by the exposure time, which in this case is considered to be 8 hours, since the Schönbein strip color scales are defined around this exposure value. Therefore,

$$[OH\ \cdot] = \frac{26.8822 ppb_{O_3} 10^{9}}{8 \cdot 3600} = 9.3341 ppb_{O_3} 10^{5} \left[\frac{molec}{cm^3 \cdot s}\right] \quad \textbf{(R11)}$$

Thus, with the complete equivalence between ozone and OH· defined, the table of paired Schönbein numbers is obtained in terms of the emission of hydroxyl radicals OH· emitted per unit volume and time, which will be called the "Monagas Variant."



GRAPHIC 4: Proposed new Monagas chart for Environmental Quality Departments based on Schönbein chart to measure OH· concentration in air (Own elaboration)

2.6 Comparison with Literature Values:

With all the information presented above, the results obtained provide a starting point for applying chromo-stoichiometric techniques to the quantification of ROS and show consistency with real environmental values measured in air (Anglada et al., 2014). This is achieved by comparing the behavior of ozone (O_3) under sunlight in two very different environments: air (gaseous phase) and the water surface (air-water interface). The table demonstrates that ozone decomposes much faster and produces many more hydroxyl radicals (OH·) when in contact with water than when it is alone in air.

TABLE 2
OZONE PHOTOLYSIS RATE CONSTANTS (J) AND OH· PRODUCTION RATES (vOH·) IN THE GAS PHASE AND AT THE AIR-WATER INTERFACE (ANGLADA ET AL., 2014)

Category	Gas Phase – J (s^{-1})	Gas Phase – vOH· ($molec·cm^{-3}·s^{-1}$)	Air–Water Interface – J (s^{-1})	Air–Water Interface – vOH· ($molec·cm^{-3}·s^{-1}$)
Calculated (this work)	3.2×10^{-5}	0.7×10^{6}	7.6×10^{-4}*	1.5×10^{10}
Calculated (this work)†	—	—	1.1×10^{-4}	0.21×10^{10}
Measured (literature)‡	3.8×10^{-5}	$0.7–10 \times 10^{6}$	—	—

The table validates the article's main thesis: water is not a passive medium. Furthermore, it generates a spectral shift. The authors discovered that when ozone is in a humid environment, due to the proximity of the water molecule, its structure changes slightly, allowing it to absorb sunlight much more efficiently (a "redshift" in its absorption spectrum). This suggests that in places with high humidity, clouds, or over the ocean, atmospheric chemistry is much more active than previously thought, as very high levels of OH· (the main reagent for degrading pollutants) are being generated right at the water's surface.

III. EXPERIMENTAL DESIGN FOR THE DETERMINATION OF ENVIRONMENTAL OXIDANTS

3.1 Test Strips:

Airborne oxidants can be detected using specially prepared paper strips moistened with a reagent, known as Schönbein paper. The Schönbein reagent strips consist of cellulose paper wipes arranged in a plastic reservoir. The strips change color in the presence of oxidizing species in the environment, with the color providing a qualitative indicator of the concentration of these oxidants.

To validate the paper wipe as a reagent carrier, it is necessary to evaluate its behavior with different concentrations of a known oxidant, such as hydrogen peroxide of a known purity. This is done by applying a couple of drops of reagent to each wipe fragment. First, the wipe is exposed to a selected control environment free of other oxidants. Then, a couple of drops of the corresponding known concentration of hydrogen peroxide are applied, and finally, the wipe is left to act for 8 hours (considering that the reactant liquid is applied directly to the reactive wipe and that an instantaneous reaction occurs, a high level of humidity is interpreted in the Monagas Variant table).

FIGURE 1: Reactive wipe (strip) with different concentrations of peroxide (Own elaboration)

On the other hand, to simultaneously ensure and rule out the possibility that the material itself (cellulose paper) from which the wipe is made reacted with the reagent and changed color in the absence of oxidants in the environment, an additional sample was added to the test as a "control." This was done by placing a reactive wipe in a container with no oxidants present and sealing it. The control wipe was then stored in a light-protected container. As can be seen in the following image, after almost a month since the test, the reactive wipe has not undergone any alteration.

FIGURE 2: Control wipe (strip) with reagent and closed in an environment without any oxidizing agent, after one month (Own elaboration)

3.2 Validation Steps:

The tests have been validated through the following steps:

1. Environmental conditions were verified to be suitable and reproducible for the required measurements. It was also verified that no other oxidizing sources were present in the environment.
2. Schönbein reagent wipes were used as easily accessible and manageable sensing elements. These were placed in the study area and then qualitatively verified (by checking the color) after 30 minutes and 8 hours.
3. Control Schönbein reagent wipes were also placed.
4. Oxidizing agent production, under controlled conditions, was evaluated for various purity ranges using the colorimetric reaction that developed and was observed on the surface of the Schönbein reagent wipes.
5. Once the results were obtained, a qualitative evaluation (by observing the color change) was performed in three ranges: Low, Medium, and High. For a rapid test of the presence of ambient oxidation of the OAF (Open Air Factor), the test wipe is placed in the environment and left for 90 minutes; for a more comprehensive test, 8 hours are allowed. The 90-minute rapid oxidation test will provide the reference results for quantitative calibration of the color techniques.

3.3 OAF Generator Validation:

Finally, to allow for future comparison with other oxidants, a study is conducted to examine the oxidative influence of hydroxyl radicals on Schönbein reagent wipes using a device that generates hydroxyl radicals from the OAF. The study is performed in a 1 m³ chamber. The status is monitored at the same time points as the previous exposures: 90 minutes and 8 hours.

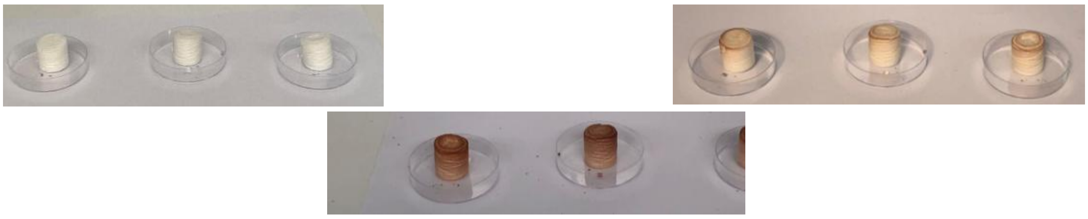


FIGURE 3: Results of the qualitative study. From left to right: test at start time, 90 min, and 8 h (Own elaboration)

The oxidation reactions are shown by the resulting color, providing percentage equivalencies for the purity of a known oxidant, such as hydrogen peroxide. The similarity in color and tone produced by different hydrogen peroxide purities coincides with the tones of the oxidations obtained under the influence of the OAF generating device.

The cellulose paper towel support, like a conventional test strip, can be used to quickly and qualitatively validate the presence of oxidants in the environment, as well as in the vicinity of devices or products that generate oxidants. Establishing this relationship allows for grouping by levels.

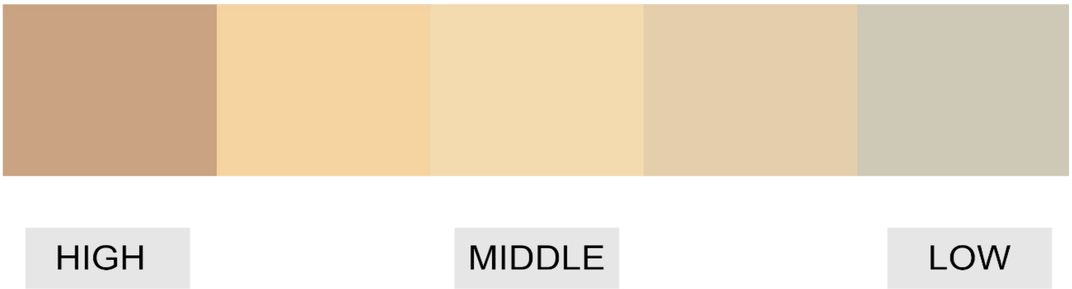


FIGURE 4: Result of the quantitative association of oxidation by OH· as a function of the color of the transition (Own elaboration)

The qualitative results obtained from the strips with colorimetric comparisons allow for the construction of a chromo-stoichiometry based on the average oxidative capacity observed in the different color ranges. This is equivalent to the oxidative capacity provided by this quantitative method, with a tolerance of approximately ±500 Kelvin. The numerical value associated with radical emission as a function of the degree of oxidation is then indicated.

3.4 Example with 17.5% Hydrogen Peroxide:

As a particular case, a photograph is shown taken for a wipe test after 90 minutes in an intrinsically humid environment, using hydrogen peroxide of 17.5% purity:

FIGURE 5: Qualitative result of the color change of a reagent strip with application of H_2O_2 at 17.5% (Own elaboration)

The quantitative value, according to the Monagas Variant, corresponding to the color obtained belongs to the HIGH oxidation level. Therefore, it is equivalent to a radical emission greater than 1.83 × 10^7 molec·cm^{-3}·s^{-1}.

IV. NUMERICAL COMPARISON AND RESULTS

4.1 Theoretical Model Results:

The relationship between the color change of potassium iodide test strips and the concentration of oxidizing species is based on a rigorous chromo-stoichiometric approach. This analysis uses the Schönbein Scale, which qualitatively correlates the observed color with the ozone (O_3) concentration in ppb under different relative humidity conditions. The quantification process begins with converting these concentrations to moles of substance and calculating the absolute humidity, essential factors for identifying O_3 as the limiting reactant in the reaction.

Based on this, the stoichiometric calculation is performed to determine the generation of hydroxyl radicals (OH·), thus obtaining an emission rate expressed in mol·cm^{-3}·s^{-1} after considering an eight-hour exposure period:

$$[OH\ \cdot] = \frac{26.8822ppb_{O_3}10^9}{8\cdot 3600} = 9.3341ppb_{O_3}10^5\left[\frac{molec}{cm^3\cdot s}\right] \qquad \textbf{(R12)}$$

*****Based on this equivalence, the Monagas Variant was constructed, which transforms a qualitative color scale into a quantitative scale of radiative emission.

In this way:

Color (qualitative) → Schönbein number → OH· emission (quantitative)

The chromaticity observed in the reactive wipes under exposure to OAF generators showed a direct correspondence with the values calculated using the Monagas Variant.

4.2 Oxidation Degree Classification:

Applying the Monagas Variant, a three-level classification was established based on OH· emission ranges:

TABLE 3
DEGREE OF OXIDATION BASED ON OH· EMISSION RANGE

Oxidation Degree	OH· Emission Range (molec·cm^{-3}·s^{-1})
HIGH	> 1.8304 × 10^7
MIDDLE	1.6762 × 10^6 – 1.8304 × 10^7
LOW	< 1.6762 × 10^6

Source: Own elaboration

4.3 Experimental Results:

Experiments conducted in a 1 m³ tank using the OAF generator demonstrated the system's remarkable responsiveness. In just 90 minutes, the color change reached a range equivalent to MIDDLE-HIGH, finally stabilizing at the HIGH level after 8 hours of exposure. Additionally, tests performed with 17.5% H_2O_2 yielded similar results, with a change in the HIGH range that allowed for an estimated equivalent emission exceeding 1.83×10^7 molec·cm^{-3}·s^{-1}.

In contrast to the activity observed in the presence of oxidizing agents, tests conducted in control environments without these elements showed no color variation, even after a 30-day period, placing its equivalent emission at the LOW level. This data confirms the robustness of the Monagas Variant, as the model allows for rapid determinations in just 90 minutes with complete technical agreement with the measurements of the extended 8-hour model. Essentially, it confirms that it is not necessary to wait for the complete cycle to obtain a reliable reading of the oxidative potential.

V. DISCUSSION

The Monagas Variant proposal transcends the purely qualitative nature of traditional tools to establish itself as a quantitative method for estimating environmental radicals. When this approach is compared with the qualitative experimental design, it is observed that the intensity of the color change on the reagent strips fully coincides with the expected theoretical emission ranges. Furthermore, the color response obtained in just 90 minutes maintains a constant proportionality with the results after 8 hours of exposure, while the stability of the reagent support is confirmed by the absence of changes in oxidant-free environments, thus guaranteeing the sensor's reliability.

From a strictly quantitative perspective, the values achieved, which are on the order of 10^7 molec·cm^{-3}·s^{-1}, are closely related to the production of hydroxyl radicals (OH·) documented in the scientific literature. Specifically, these data align with the ozone photolysis at air-water interfaces described by Anglada et al. (2014) and with the values reported under natural high Open Air Factor (OAF) conditions. This strong consistency between the stoichiometric model, experimental results, and scientific precedents reinforces the validity of the proposal. In this context, the fact that ozone always acts as the limiting reactant technically justifies the direct reinterpretation of Schönbein's original chromatic scale in terms of radical emission.

The practical implications of this work are significant. The Monagas Variant provides an accessible, low-cost tool for monitoring environmental oxidative capacity and assessing OAF in indoor spaces. The ability to obtain reliable readings in just 90 minutes, rather than the traditional 8 hours, makes this method particularly valuable for rapid assessments in healthcare facilities, commercial buildings, and other indoor environments where air quality is critical.

VI. CONCLUSIONS AND FUTURE PROSPECTS

In conclusion, this research has successfully developed a robust chromo-stoichiometric model that transforms the traditional Schönbein Scale into a quantitative analytical tool. Thanks to the Monagas Variant, it is now possible to estimate OH· emission (expressed in molec·cm^{-3}·s^{-1}) by simply observing a color change, allowing for efficient classification into three intensity levels (LOW, MIDDLE, and HIGH) with a response time of only 90 minutes. This advancement translates the complexity of stoichiometry to a visual scale, offering an accessible protocol for maintenance and monitoring teams without the need for expensive laboratory equipment.

The results obtained demonstrate consistency with the scientific literature on atmospheric radical production, positioning this system as an extraordinary bridge between qualitative observation and quantitative estimation. Its accessibility, reproducibility, and low cost make it an ideal solution for monitoring ambient oxidation and assessing the Open Air Factor in indoor spaces, where accuracy and speed are crucial.

Finally, this work lays the groundwork for future research. The scientific community is encouraged to continue refining the methodology using more precise photometric and colorimetric sensors. This technical evolution would allow a shift from visual to digital interpretation, paving the way for the development of portable tools and mobile applications. Integrating this methodology into everyday devices would bring radical monitoring to an unprecedented level of ubiquity and accuracy in the field of environmental health.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper.

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