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EMERGING SCIENTIFIC DIRECTIONS IN PLASMA TECHNOLOGY FOR FOOD DECONTAMINATION

Mario Coccia and Ugo Finardi

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Emerging scientific directions in plasma technology for food decontamination

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ABSTRACT: The purpose of this research is to analyze the evolutionary growth of knowledge in non-thermal plasma technologies applied for food decontamination in order to pinpoint emerging scientific directions. The sample uses 22,836 articles and 2,282 patents from Scopus/SciVerse database in order to calculate the rate of scientific and technological growth that may detect emerging technological trajectories and applications. Results show that emerging plasma technology for food decontamination are mainly cold atmospheric pressure plasma and gas plasma. Moreover, plasma seems to be a promising technology for decontamination of fresh food from bacteria Staphylococcus Aureus, Listeria Monocytogenes and Pseudomonas Aeruginosa, respectively. However, key limitations are the relatively early state of technology development, and the largely unexplored impacts of non thermal plasma on nutritional qualities of treated foods. Nevertheless, this technology shows promise for bio-decontamination and is the subject of active research to enhance efficacy and open up crucial opportunities to industrial and social safety.

Keywords**:** Plasma, Non-Thermal Plasma, Technological Innovation, Technological Trajectories, Decontamination, Sterilization, Food, Bacteria.

JEL Codes: L 66, O30

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The authors in parentheses (MC: Mario Coccia and UF: Ugo Finardi) have made substantial contributions to the following tasks of research: Conception (MC); Design (MC and UF); theoretical framework (MC & UF); acquisition of data (UF); modelling and analysis of data (MC); interpretation of data (MC and UF); drafting of the manuscript (MC and UF); critical revision of the manuscript for important intellectual content (MC); statistical analysis (MC), supervision (MC). The usual disclaimer holds, however.

SUMMARY

1. INTRODUCTION

In recent years, the demand for fresh food has steadily been increasing mainly due to healthier life-style. Since fresh food products are often consumed raw, they have the risk of contamination by pathogenic microorganisms that also increase the risk of infection or intoxication (Stoffels et al., 2006). Conventional food preservation techniques for highly perishable food products are limited and have fostered the development of new process technologies, such plasma technology that can operate at ambient pressure to decontaminate food (non thermal plasma). This innovative non thermal plasma technology may have a lower impact on the quality and fresh appearance of food products, while simultaneously effectively inactivates micro-organisms. In fact, there can be vital reductions, applying plasma technology, for pathogens such as Salmonella, Escherichia Coli, Listeria Monocytogenes, and Staphylococcus Aureus (*cf.* Fernández and Thompson, 2012; Fröhling et al., 2012; Noriega et al., 2011, p. 1294ff; Ragni et al., 2010). Although the high promise of plasma technology and the active scientific research in this research field, patterns of plasma technological innovations for food applications are poorly explored and under researched (cf. Friedman, 2008). Non thermal plasma technologies for food decontamination are at the early phase of technological development and to analyze the emerging technological trajectories can play a vital role to pinpoint new fruitful scientific directions for industrial applications that improve food products for society (Coccia, 2004, 2005a, 2005b, 2012)[1]. The present study analyzes the evolutionary growth of scientific and technological knowledge of key plasma technologies and research fields by some models based on scientific outputs (articles and patents). In particular, the purpose of this paper is to pinpoint new directions of plasma technological trajectories applied for food decontamination and detect, by rates of knowledge growth, which pathways precede faster than others.

2. THEORETICAL BACKGROUND: PLASMA TECHNOLOGY FOR FOOD DECONTAMINATION

Plasma can indicate a collection of charged particles (an ionized gas) in physicochemical science and also the liquid component of blood in medicine. This study focuses on plasma as a neutral ionized gas. It is constituted by particles in permanent interaction; the particles include photons, electrons, positive and negative ions, atoms, free radicals and excited or non-excited molecules (Moreau et al., 2008, p. 611). Friedman (2008, p.1) argues that: “ionized gas is usually called plasma when it is electrically neutral ... and contains a significant number of electrically charged particles, sufficient to affect its electrical properties and behaviour”. Vast technological applications of plasma physics and chemistry are: TV, mobile phones, synthetic fibers, ozone-plasma technology for potable water, gas lasers, air-cleaning systems, food containers, hydrogen production, fuel-cell technology, etc. Some new technologies are also based on plasma

[1] Cf. Coccia at al., 2012 for detecting emerging research fields in nanotechnology.

nanotechnology and dusty plasma (*i.e.* containing nanometre or micrometer-sized suspended particles), plasma aerodynamics and plasma applied in micro-electronics. Expected applications are also in biology and medicine: surgery, sterilization of devices, destruction of pathogens, tissue engineering and prevention medicine (Friedman, 2008, *passim*; Coccia and Finardi, 2013).

Plasma can be thermal or non-thermal, depending on its method of creation. *Thermal plasmas* are obtained at high pressure and with a substantial power (up to 50 MW); "Thermal plasma processes have a long history of industrialization, of which a notable application is coating metallic substrates with hydroxyapatite (HA) for orthopaedic implantation. Despite its industrial efficiency, thermal plasma deposition results in undesirable changes to thermally sensitive substrates such as HA" (Tan et al., 2012). *Non-thermal plasmas* are obtained at lower pressures and use less power. Recently, a new plasma technology can represent a third category: *non-thermal atmospheric plasma*, also called cold plasma. This plasma is intermediate between the two others and in general is included in the set of the non-thermal plasmas because is formed near atmospheric pressure and ambient temperature. "The temperature of non-thermal atmospheric plasma […] is low, at around room temperature" (Kim et al., 2010, p. 530).

Non-thermal plasmas are divided in two main typologies: *a*) "direct plasma treatment": the sample is in direct contact with the plasma; on the other hand, *b*) indirect plasma treatment is represented by atmospheric pressure plasma jets. This is also known as afterglow and the sample is placed at some distance from the plasma (Fridman et al., 2007; Laroussi, 2009).

Plasma interaction with living matter is at present a cutting edge subject of plasma research and development driven by the demand, in recent years, for fresh food that has been increasing mainly due to a healthier life style. The risk of contamination by spoilage and pathogenic microorganisms is of concern because most of these products are consumed raw, without further cooking. As current decontamination technologies have limited effects (Carvalho et al., 2010), hence there is the need for an effective technology within commercial constraints. Until relatively recently, plasmas could only be generated under vacuum at temperatures inappropriate for food treatments. The advent of non thermal gas plasmas at ambient temperature and atmospheric pressure makes these innovative technologies suitable for the decontamination and preservation of foods.

This has increased the interest by food industry in low-temperature innovative processes for food preservation whilst limiting the impact of processing on nutritional and sensory quality, and without compromising safety (Fernández and Thompson, 2012). Moisan et al. (2001, p. 1) argue that an ionized gas (plasma) to: "achieve sterilization is an alternative to conventional sterilization means as far as sterilization of heat-sensitive materials and innocuity of sterilizing agents are concerned".

The applications and analysis of non-thermal plasma technologies to bacterial control and bio-decontamination are crucial to industrial and social safety. Gas plasma (as ionized gas containing free electrons and neutral reactive species, *e.g.* atoms, molecules and radicals) generates a main germicidal effect. In fact, gas plasma offers an original alternative to sterilization because of intrinsic properties of this approach. In particular, the method consists in exposing microorganisms to species stemming from an electrical discharge in a gas. Three mechanisms are involved in the plasma inactivation of microorganisms: "(A) direct destruction by *UV irradiation* of the genetic material of microorganisms; (B) erosion of the microorganisms atom by atom, through *intrinsic photodesorption* by UV irradiation to form volatile compounds combining atoms intrinsic to the microorganisms; (C) erosion of the microorganisms, atom by atom, through *etching* to form volatile compounds as a result of slow combustion using oxygen atoms or radicals emanating from the plasma" (Moisan et al., 2001, p. 1, original emphasis). The operating conditions of the plasma have to be set for an efficient inactivation of microorganisms, while minimizing the damage of materials subjected to the treatment.

In order to decontaminate foods without bringing about undesired changes, gas plasmas should ideally be operated at or near room temperature (Perni et al., 2008). Ragni et al. (2010) show a device that generates gas plasma at atmospheric conditions applied for the decontamination of shell eggs with *Salmonella*[2] *Enteritidis* and *Salmonella Typhimurium*. Results display no significant negative effects of the gas plasma on the egg quality traits. Other main applications concern poultry carcasses that can be contaminated by Salmonella, Campylobacter and Listeria Monocytogenes; Noriega et al. (2011, p. 1294ff) discuss as gas plasmas generated at atmospheric pressure and ambient temperatures can be used for decontamination of skin and muscle inoculated with *Listeria Innocua*[3] in poultry products. The efficacy of gas plasma treatment in this case depends on surface topography. Instead, Rød et al. (2012, p. 233 and 237) show the application of cold atmospheric pressure plasma for decontamination of sliced ready-to-eat meat products inoculated with *Listeria Innocua*.

This sporadic food borne illness has a growing incidence in many European countries for ready-to-eat food products, meat and seafood delicatessen. Results show that indirect cold atmospheric pressure plasma treatment can reduce *Listeria Innocua* on the surface of pre-packed sliced ready-to-eat food products, though plasma treatment increased lipid oxidation that may constitute an issue in some products. Plasma application also shows a high potential in food processing and Fröhling et al. (2012) analyze how non-thermal plasma treatment has also the potential to disinfect and sterilize the heat sensitive materials and products with inactivation effects on Gram-positive Listeria Innocua and Gram-negative Escherichia Coli[4] inoculated on polysaccharide gel using the plate count method and flow cytometry. Fernández and Thompson (2012) analyze cold atmospheric plasmas applied to kill

[2] Salmonella is a genus of rod-shaped, Gram-negative, non-spore-forming, predominantly motile enterobacteria.

[3] Listeria Innocua is one of the six species belonging to the genus Listeria. It is found in the environment such as soil and food sources. It is a rod-shaped Gram-positive bacterium. Listeria Innocua is similar to other family members, e.g. the pathogenic Listeria Monocytogenes

[4] Escherichia Coli is a Gram-negative, rod-shaped bacterium that is commonly found in the lower intestine of warm-blooded organisms (endotherms).

Salmonella cells in a short run. The successful results suggest the use of cold atmospheric plasmas for food preservation, though the factors involved in the inactivation of Salmonella remain to be fully characterized (p. 5). Yang et al. (2009) confirm the advantage of plasma sterilization in the possibility to achieve a high level of sterilization at low temperatures with no residual toxicity. They analyze the sterilization of the *Pseudomonas Aeruginosa*[5] on the polyethylene terephthalate (PET) sheets. "The analysis of O_2 plasma sterilization mechanisms shows that in the active discharge area, intense etching action of electrons and ions on cell membrane engenders bacteria death, here function of oxygen radicals and UV radiation are slight; in the afterglow area and remote area, attacking polyunsaturated fatty acids in the cell membrane by high concentration oxygen radicals becomes the main factor of bacteria death" (Yang et al., 2009, p. 8964). This sterilization method is easy to apply and requires significantly less exposure time than other traditional methods.

Instead, Grzegorzewski et al. (2011) analyze the interactions of plasma immanent reactive species with secondary plant metabolites, exposing lamb's lettuce (*Valerianella Locusta*) to an atmospheric pressure plasma jet. "Whereas phenolic acids showed a slow decrease, flavonoids are quickly degraded. The degradation is not caused from the combined interaction of various reactive plasma species. For *V. Locusta*, on the contrary, phenolic acid levels were reduced while a strong increase of diosmetin has been found. Leaf surfaces were significantly affected by plasma treatment, leading to erosion phenomena of the upper epidermis.

As a result, mono- and polyphenols are oxidized into volatile compounds which diffuse to the surface and desorb. This leads to comparably low levels of mono- and polyphenolics upon plasma exposure relative to concentrations obtained from UV-C radiation and temperature simulating experiments" (p. 2289, original emphasis).

This background shows that non-thermal plasma technology for food decontamination is the subject of active scientific research; nevertheless main directions of technological trajectories have not been explored yet. Next section describes a methodology to analyze this topic in order to pinpoint emerging technological applications for fruitful effects on food industry and societies.

3. RESEARCH DESIGN

Grupp (2000, p. 143) argues that: "innovation literature centres more on technical advance and less on scientific change". As a matter of fact, it is important to ascertain that advances in scientific literature can be considered as an ice-breaker for new scientific research fields that underpin new pathways for emerging technologies. In order to investigate the intensity of scientific and technological research in plasma technologies for food decontamination and preservation that may drive future technological pathways, it has been carried out a search of critical keywords on the databases Scopus (2012) and SciVerse (2012) by Elsevier. Data mining has been performed with a series of queries based on keywords and Boolean operators and

[5] Pseudomonas Aeruginosa is a common bacterium that can cause disease in animals, including humans. It is found in soil, water, skin flora, and most man-made environments throughout the world.

focused on time horizon 1970 (first year) – 2011. Data on scientific products, which indicate a proxy of scientific activities in these research fields, are retrieved by the “Advanced search” window of Scopus (2012) database. In particular, keywords of non-thermal plasma technologies in this vital scientific field are searched using the "TITLE-ABS-KEY" code (which stands for "Search the keyword in Title, Abstract or Keywords". As a general rule data mining has been performed including keywords into quotation marks: i.e. search for the exact phrase). As far as the technological activity is concerned, it is measured by patents. The queries are performed in the SciVerse (2012) database using and selecting "Patent Offices" as an option for the source of documents. SciVerse by Elsevier contains patents from World Intellectual Property Organization, European Patent Office, United States Patent and Trademark Office, Japan Patent Office and several European patent offices (Germany, UK, and France). The use of quotation marks is similar as in the case of scientific output. Data on patents indicate a proxy of technological output[6].

Statistical analysis is based on two samples represented by 22,836 articles (1970-2011 period) and 2,282 patents (mainly 1997-2011) from Scopus/SciVerse. The analysis also considers the citations of papers to better evaluate the evolutionary growth of these research fields.

The vast sample (articles + patents) is the basis to apply some models for analyzing the scientific and technological pathways of plasma technologies (mainly non-thermal plasma technology) for food decontamination that provide main insights about emerging scientific and technological directions.

In particular, as scientific and technological advances in plasma technology have been accelerating, a main aspect is to measure and analyze the *rate of scientific and technological advance* by the growth in number of articles and patents to assess the evolutionary growth of knowledge over time. An *exponential* model is a fruitful approach to measure this trend considering the following *assumptions* (cf. Coccia, 2012):

1: ${}_0P$ is the number of articles/patents at 1970 (1997 for patents)

2: ${}_tP$ is the number of articles/patents at 2011

3: t is the analyzed period

4: articles are a proxy of the scientific activity, whereas patents are a proxy of the technological activity of these research fields.

The model is:

$${}_tP = {}_0P \cdot e^{rt}$$

where e is the base of natural logarithm (2.71828…).

Hence $\frac{{}_tP}{{}_0P} = e^{rt}$; $\quad Log \frac{{}_tP}{{}_0P} = r \cdot t$;

$$r = \frac{Log\left(\frac{{}_tP}{{}_0P}\right)}{t}. \qquad [1]$$

[6] Technology is based on inventions and innovations. Invention is a commercially promising product or service, based on new science and/or technology that meet the requirements for a patent application and/or for which the patent is already granted. On the other hand, innovation, which already has a valid and granted patent, is the successful entry of a new science or technology-based product into a particular market. In particular, innovations are protected by patents, which indicate the current innovation of industries and also commercially promising inventions (cf. Coccia, 2009; 2010; 2011; 2012a).

r= rate of scientific (or technological) advances

This method can offer an analytical framework for understanding the fruitful directions of technological trajectories for food decontamination based on (non-thermal) plasma technologies. In addition, the data have also been analyzed by econometric modelling based on time series to better understand new directions and compare the results with previous approach (Eq.[1]). As some distributions have not normality, it has been applied a logarithm transformation to have apt distributions for parametric estimates.

In particular, the functional relationship is: Scientific output of non thermal plasma applied for decontamination of bacterium $= f$ (Time)

The specification is based on simple regression models:

$$y_{i,t} = \lambda_0 + \lambda_1 Time + u_{i,t} \qquad \text{(linear model)} \quad [2]$$

$$Ln\, y_{i,t} = \lambda_0 + \lambda_1 Time + u_{i,t} \qquad \text{(growth model)} \quad [3]$$

where the i subscript indicates the country and t the time, $u_{i,t}$ = error term

These equations is estimated by Ordinary Least Squares (OLS), using the statistics software SPSS (Statistical Package for the Social Sciences). Results show R Square statistic that is a measure of the strength of association between the observed and model-predicted values of the dependent variable. The large R Square values indicate strong relationships for models. Adjusted R Square is a "corrected" value because R Square statistic penalizes models with large numbers of parameters. The ANOVA table tests the acceptability of the model from a statistical perspective: ANOVA table is a useful test of the model's ability to explain any variation in the dependent variable. The significance value of the *F statistic* is less than 0.05, which means that the variation explained by the model is not due to chance.

4. RESULTS

First of all, it is important the comparison of the evolutionary scientific growth of non-thermal plasma with other key scientific fields. Data show the high rate of scientific advance of non thermal plasma, equal to 19.06%, in comparison to other driving scientific fields, such that it ranks at the 2nd position of knowledge growth (considering scientific outputs) after Spintronics (table 1).

Table 1: Scientific outputs and rates of growth of emerging scientific fields (Data source SciVerse, 1999-2011 period)

Research Fields	Article	Books	Related works	Total	*r%* - Rate of scientific advances (Eq. [1])
Spintronics	4474	122	49	4645	44.48
Non-thermal plasmas	1041	9		1050	19.06
Complementary Metal-Oxide-Semiconductor	2638	196	108	2942	18.74
Silicon quantum	639	31	11	681	8.79
Low-pressure plasma	2599	59	20	2678	2.89
Epitaxy	58574	1231	385	60190	1.41
Thermonuclear plasma	296	18	4	318	1.03

Table 2: Rates of the scientific growth of scientific fields in non thermal plasma for food decontamination (Data based on scientific articles by Scopus, 2012)

Occurrences of articles (combined keywords)	Total Articles	r = Evolutionary growth of scientific knowledge in % (Eq. [1])	Period
Cold atmospheric pressure plasma	31	39.96	1983-2011
Cold atmospheric plasma	65	18.31	1970-2011
Gas plasma AND decontamination	25	17.92	2006-2011
Microwave plasma	7093	10.56	1999-2011
Etching AND plasma AND decontamination	35	4.33	1990-2011
Afterglow AND plasma	1411	2.79	1970-2011
Germicidal effect AND plasma	21	32.43	2001-2011
Plasma AND decontamination	1393	11.26	1970-2011
Inactivation AND plasma AND decontamination	65	8.96	1970-2011
Pseudomonas Aeruginosa AND plasma	1208	6.65	1996-2011
Escherichia Coli AND plasma	6727	5.71	1970-2011
Salmonella AND plasma	1072	2.98	1990-2011
Escherichia Coli AND plasma AND decontamination	134	10.35	1983-2011

Bacterial control and decontamination by non-thermal plasmas have the origin in 1990s to find alternative technologies for the sterilization of heat-sensitive materials.

Table 2 shows evolutionary rates of growth of non thermal plasma for food decontamination, which are a strong indicator to pinpoint emerging directions of research fields and technological trajectories that may play a vital role for food industry and societies.

As far as the typologies of plasma technology are concerned, the highest scientific rate of growth is by cold atmospheric pressure plasma (about 40%), followed by gas plasma (roughly 18%) and microwave plasma (10.85%), instead the evolutionary rate of scientific growth of etching and afterglow is lower (table 2).

The rate of scientific growth of plasma technology applied with germicidal effect is high and equal to 32.4% (table 2).

Table 1 also shows the detection of the technological trajectories of plasma technology applied to decontaminate food from different bacteria.

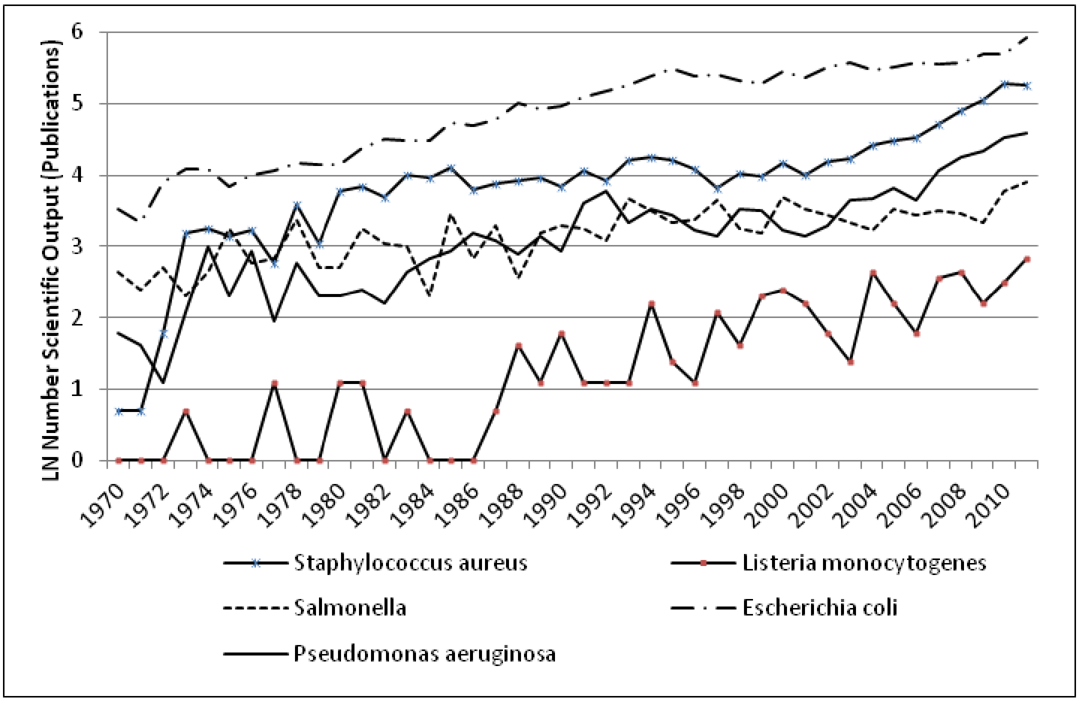

Figure 1: Trends of scientific knowledge growth (publications) of non thermal plasma for decontamination of different bacteria

In particular, the higher rate of scientific growth is represented by plasma technology applied to decontaminate from Staphylococcus Aureus[7] (about 11%), Listeria Monocytogenes (7.5%) and Pseudomonas Aeruginosa (5.7%). The plasma technology applied against the bacteria Salmonella has a lower rate of scientific growth because the scientific research is in progress.

Figure 1 shows the growing trends of non thermal plasma for decontamination of different bacteria measured by publications. In particular, the higher trends (absolute value) are represented by decontamination of Escherichia Coli and Staphylococcus Aureus; in addition, Fig.1 also displays the high scientific knowledge growth of non thermal plasma applied for decontamination of Pseudomonas Aeruginosa. Trend of Salmonella has a stable trend over time, whereas Listeria M. has lower values but a growing trend.

As far as geographic distribution of scientific production in this field is concerned, table 3 shows the top 10 countries for the number of scientific products related to the use of non thermal plasma for decontamination of different kind of bacteria.

[7] Staphylococci are Gram-positive spherical bacteria that occur in microscopic clusters resembling grapes. Bacteriological culture of the nose and skin of normal humans invariably yields staphylococci. Two pigmented colony types of staphylococci are: *Staphylococcus Aureus* (yellow) and *Staphylococcus Albus* (white). S. Aureus can cause a range of illnesses: skin infections, pneumonia, meningitis, osteomyelitis, endocarditis, bacteremia, sepsis etc.

Table 3: Top 10 countries per number of scientific products (presenting at least one affiliation) concerning non-thermal plasma applied to specific bacteria

Pseudomonas Aeruginosa	1st year 1964	Escherichia Coli	1st year 1945	Salmonella	1st year 1948	Staphylococcus Aureus	1st year 1944	Listeria Monocytogenes	1st year 1972
USA	441	USA	2466	USA	451	USA	884	USA	110
Japan	192	Japan	716	Japan	91	Japan	338	Germany	26
Germany	98	Germany	555	Germany	75	Germany	204	France	25
UK	76	UK	475	UK	70	UK	172	UK	16
France	73	France	337	Italy	44	France	121	Japan	14
China	51	China	312	Canada	41	China	111	The Netherlands	9
Canada	49	Canada	307	France	38	Sweden	93	Canada	8
Italy	44	Sweden	242	The Netherlands	31	The Netherlands	87	South Korea	7
The Netherlands	37	The Netherlands	237	China	18	Belgium	80	Italy	7
Australia	32	Italy	160	South Korea	17	Spain	80	Switzerland	6

The US has the leadership of all these research activities, followed by Japan in 4 out of 5. Other leading countries are Germany (3rd in 4 research topics and 2nd for Listeria Bacterium), the UK and France. Italy is 5th in the case of Salmonella.

In order to assess the trend of scientific production, the number of citations is considered. As Scopus counts citations from 1996 onwards, only scientific products from 1996 to 2012 have been considered. Table 4 reports for each bacterium the number of Total citations; the number of scientific products published in years 1996-2012; the average number of received citations per each product; the average number of received citations per year.

While “Listeria” leads for the number of citations per article, “Escherichia Coli” has the highest value for the number of citations per year, as well as for the number of scientific products.

Table 4: Citations concerning non-thermal plasma applied to specific bacteria 1996-2012 period

	Pseudomonas Aeruginosa	Escherichia Coli	Salmonella	Staphylococcus Aureus	Listeria Monocytogenes
Total received citations	13,054	101,853	14,769	27,563	6,785
Scientific products	849	4455	583	1790	186
Average received citations per product	15.38	22.86	25.33	15.40	36.48
Received citations per year	767.88	5,991.35	868.76	1,621.35	399.12

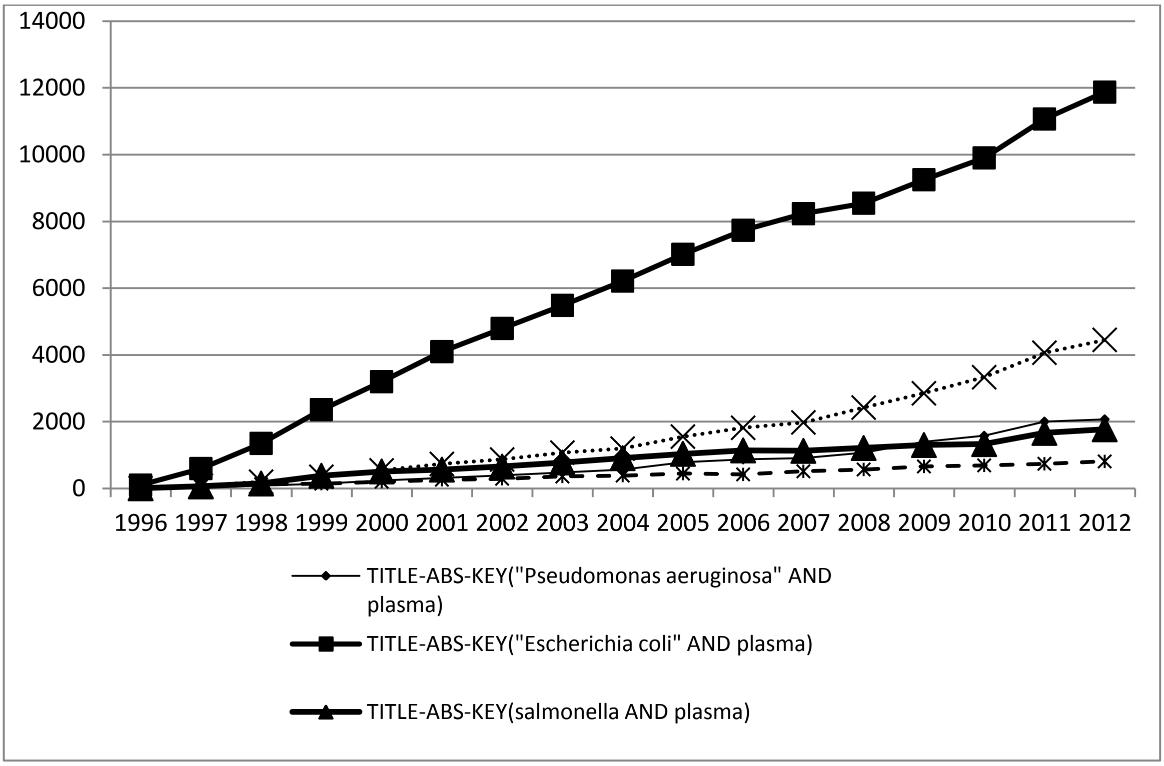

Figure 2: Trends of citations concerning non thermal plasma for decontamination of different bacteria

Figure 2 presents a further interesting result: the evolutionary growth of knowledge of the citations per year per bacterium. All five research fields present a rather linear trend. The number of citations for "Escherichia Coli" presents the highest trend; the second, "Staphilococcus Aureus", is lower, while the other three trends are much lower. Thus, while scientific production for "Escherichia Coli" is the most copious and the most cited, "Listeria" presents a higher rate of citations per product and is feasibly also very active.

Table 5: Descriptive Statistics of scientific output concerning non thermal plasma for decontamination of different bacteria over time

Descriptive Statistics	Staphylococcus Aureus	Listeria Monocytogenes	Salmonella	Escherichia Coli	Pseudomonas Aeruginosa
Mean	60.88	5.00	25.52	160.17	28.76
Std. Deviation	43.24	4.52	9.37	90.31	22.17
Skewness	1.63	0.99	0.226	0.24	1.63
Kurtosis	3.11	0.023	–0.314	–1.006	2.63

Table 5 shows descriptive statistics and that some distributions are not normal; in this case the logarithmic transformation is an apt approach to have normal distributions and apply parametric estimates for analyzing by econometric models these time series. We apply different models (growth or linear) according to the structure of data. The relationships are estimated by Ordinary Least Squares (OLS) using SPSS statistics software. The first thing to be said about results is that the models in table 4 explain a high variance in the data (see adjusted R square). In addition, the parametric estimates of these models are unbiased, and the significance and the overall explanatory power of coefficients are excellent (table 6).

Table 6 shows that the higher coefficient of regression is given by non thermal plasma applied for decontamination of Staphylococcus Aureus, Escherichia Coli and Pseudomonas Aeruginosa. In particular, data show that scientific outputs concerning application of non thermal plasma for decontamination have an expected increase of approximately 6.6% per year for Staphylococcus Aureus, 5.4% for Escherichia Coli and 5.7% for Pseudomonas Aeruginosa. Lower increase per year is represented by Salmonella bacterium. As far as Listeria Monocytogenes is concerned, in this case it is applied a linear model: an additional year increases the expected number of publication by somewhat more than 0.30 scientific outputs. Appendix shows the curve estimated per different typology of bacterium.

Table 6: Parametric estimates considering scientific outputs (articles) over 1970-2011

Dep. variable / Models	Estimated relationship		Goodness of fit	ANOVA	Bacterium
1. *lnStaAu* y_t=	-122.7^{***}	$+ 0.064\, x_t^{***}$	R^2 *adj =0.66*	*F=80.54 (sig.0.00)*	*Staphylococcus Aureus*
Growth	(14.1)	(0.007)	*S=0.56*		
2. *lnPseAeru* y_t=	-110.14^{***}	$+ 0.057\, x_t^{***}$	R^2 *adj =0.80*	*F=161.61 (sig.0.0)*	*Pseudomonas Aeruginosa*
Growth	(8.91)	(0.004)	*S=0.35*		
3. *lnEschColi* y_t=	-102.36^{***}	$+ 0.054\, x_t^{***}$	R^2 *adj =0.93*	*F=543.25 (sig. 0.0)*	*Escherichia Coli*
Growth	(4.60)	(0.002)	*S=0.18*		
4. *lnSalmo* y_t=	-46.69^{***}	$+ 0.025\, x_t^{***}$	R^2 *adj =0.57*	*F=54.49 (sig.0.00)*	*Salmonella*
Growth	(6.75)	(0.003)	*S=0.27*		
5. *LisMon* y_t=	-605.97^{***}	$+ 0.307\, x_t^{***}$	R^2 *adj =0.69*	*F=91.32 (sig.0.00)*	*Listeria Monocytogenes*
Linear	(63.94)	(0.032)	*S=2.52*		

Note: The independent variable is time; The dependent variable is the number of scientific publications (over 1970-2011) of non thermal plasma applied for decontamination of a type of bacterium. The second column is the estimate of the constant. Underneath it, in parentheses, its standard error. The third column is the estimate of β. Underneath it, in parentheses, its standard error. The fourth column has adjusted R^2 of the regression and below it, the standard error of the regression. The fifth column has the results of the Fisher test, to its right the significance. In the last column the typology of bacterium decontaminate by non thermal plasma. t=time; *** Parameter is Significant at 0.001.

Table 7: Rates of technological growth of emerging scientific fields in non thermal plasma for food decontamination (Data based on patents by SciVerse, 2012)

Occurrences of Patents over 1997-2011 (combined keywords)	Total Patents 1997-2011	Total patent (included patents before 1997)	r = Evolutionary growth of technological knowledge in % (Eq. [1])
Plasma AND decontamination	649	712	2.08
Afterglow AND plasma	78	83	5.79
Microwave plasma	1066	1369	4.16
Inactivation/decontamination AND plasma	8		
Glow discharge plasma AND decontamination	2		
Listeria Monocytogenes AND plasma	0		
Staphylococcus Aureus AND plasma	22	30	Not available
Salmonella AND plasma	5	7	Not available
Escherichia Coli AND plasma	17	32	Not available
Pseudomonas Aeruginosa AND plasma	4		Not available

As far as the patents are concerned, there are a lot of missing values since non-thermal plasma technology for food decontamination is in infancy phase and in the majority of cases it is not possible to calculate the evolutionary rate of technological growth. Data show the high number of patents in microwave plasma, more than 1,000 units, whereas for afterglow are about 80 over 1997-2011. Table 7 shows the number of patents connected to plasma technology for decontamination of some typologies of bacteria: about 30 patents in the field of Staphylococcus Aureus and Escherichia Coli decontamination, instead Salmonella has between 5 and 7 patents (it depends on data pre- and post- 1997). The rate of technological growth shows for afterglow a higher value than microwave plasma (5.8% vs. 4,2% respectively). Afterglow, as indirect plasma treatment, may be an apt technology since food sample is placed at some distance from the plasma in order to preserve nutritional qualities and fresh appearance of food products.

5. DISCUSSION AND CONCLUDING REMARKS

The consumption of fresh food has become increasingly popular but this is associated to an increased risk of infection or intoxication due to contamination with pathogenic bacteria (Grzegorzewski et al., 2011). Conventional food preservation techniques for highly perishable food products are limited, thus fostering the development of new process technologies, among which non thermal plasma that can operate at open air at ambient pressure and are easily adjustable to treat large areas directly throughout the production line. Since they operate at room temperature, they have a minor impact on the quality and fresh appearance of food products, while simultaneously plasma inherent UV and vacuum UV radiation effectively inactivates microorganisms (Grzegorzewski et al., 2011).

The present study shows the intensive evolutionary growth of scientific research in plasma technology applied for food decontamination. In particular the empirical evidence, based on scientific articles and patents that are leading indicators of evolutionary growth of the knowledge, shows the following vital results:

- the emerging plasma technology for food decontamination, measured by the rate of scientific growth, is both cold atmospheric pressure plasma and gas plasma.
- if the technological rate of growth is considered (measured by patents), afterglow plasma shows a higher rate than microwave plasma, although the latter has a higher number of patents. For other plasma technologies and relative applications there are several missing values.
- for what about the bacteria species, using scientific rate of growth, non thermal plasma shows to be a promising and effective technology for the decontamination from Staphylococcus Aureus, Listeria Monocytogenes and Pseudomonas Aeruginosa, respectively. The rate of scientific growth in the studies concerning decontamination of food products from Escherichia Coli and Salmonella is lower. Instead, with regression models, the high scientific growth over time is Pseudomonas Aeruginosa, Escherichia Coli and Staphilococcus Aureus. A lower coefficient of regression is by application of non thermal plasma for decontamination of Salmonella bacterium.
- While “Listeria” leads for the number of citations per article, “Escherichia Coli” has the highest value for the number of citations per year, as well as for the number of scientific products. The number of citations for “Escherichia Coli” presents the highest trend; the second, “Staphilococcus Aureus”, is much lower. Thus, while scientific production for “Escherichia Coli” is the most copious and the most cited, that for “Listeria”, presenting a higher rate of citations per product, is feasibly also very active.

The promising applications of non-thermal technologies for food decontamination is because plasma reactive species do not penetrate into the food, and modifications of compounds would only occur on the food surface (Fernández and Thompson, 2012). In addition, non-thermal plasmas are emerging and promising technologies both efficient and cheap for decontamination. In fact, “Discharges at atmospheric pressure and at low temperature make the decontamination process practical, inexpensive and suitable for applications when product preservation is desired.” (Ragni et al., 2010, p.125). “The results appeared very promising, particularly in comparison with risky methods such as those employing toxic gas” (Moreau et al., 2008, p. 612).

However, many questions concerning the species of antimicrobial compounds generated during plasma discharge and their specific role in the mechanism of microbial inactivation still remain to be addressed.

A more complete understanding of the factors involved in inactivation by this emerging technology will enhance its implementation. Moreover, the role of cell structure, physiology and bacterial stress resistance mechanisms involved in plasma resistance is also poorly understood at the moment. In fact, the analysis of properties of the cold plasma treated products and more information about its nutritional and chemical effects are also necessary to determine to what extent this process affects product quality and shelf-life (Fernández and Thompson, 2012). The antimicrobial effectiveness of non-thermal plasma is scientifically accepted but the effects of plasma treatments on plant food with regard to nutritional value are not yet sufficiently investigated (Grzegorzewski et al., 2011). It is therefore important to elucidate these different effects before establishing non-thermal plasma as a mild and safe alternative to conventional food processing technology.

It is also important to note that current socio-economic changes of nutrition habits of population, more and more based on fresh food for healthy life style, can be supported by non-thermal plasma, which this study has showed is a very active research field in opening up new opportunities for agriculture and food industry. Some key steps for effective industrial applications of non-thermal plasma technology in the value chain are the definition of the plasma itself and its operating conditions, the resistance of micro-organisms and the effect desired on food products. These topics are poorly explored (Moreau et al., 2008, p. 612). We think that the key limitations for cold plasma are due to the relatively early state of technology development, the variety and complexity of the necessary equipment, and the largely unexplored impacts of cold plasma treatment on the sensory and nutritional qualities of treated foods.

Nevertheless, this emerging scientific area of plasma technology shows promise for food decontamination and is the subject of active research to enhance efficacy to industrial and social safety.

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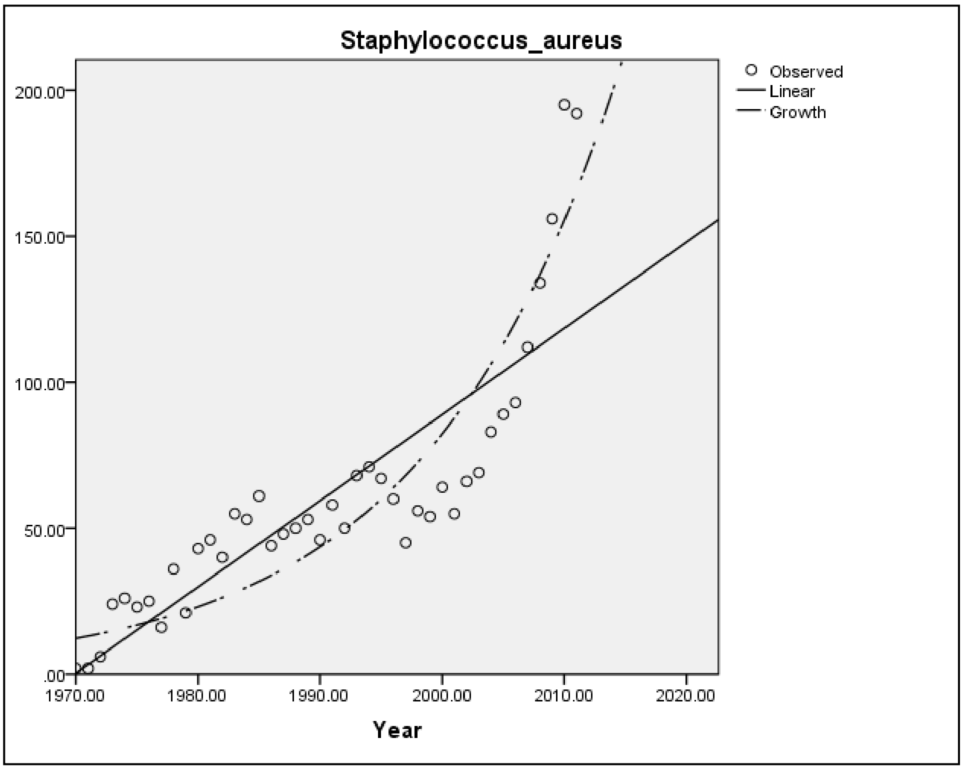
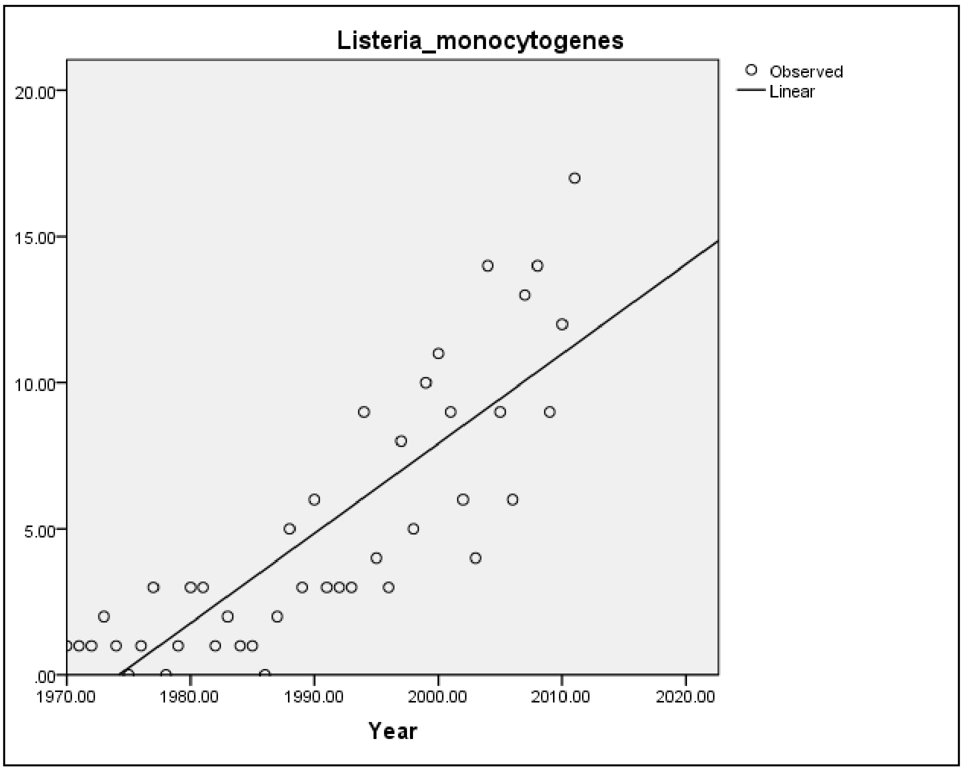
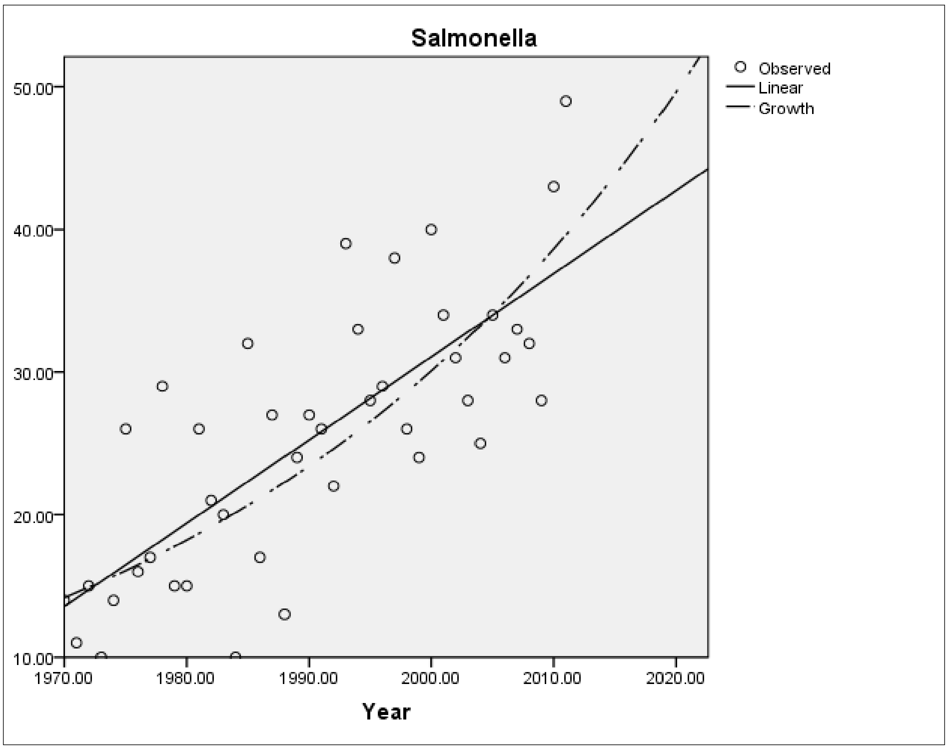
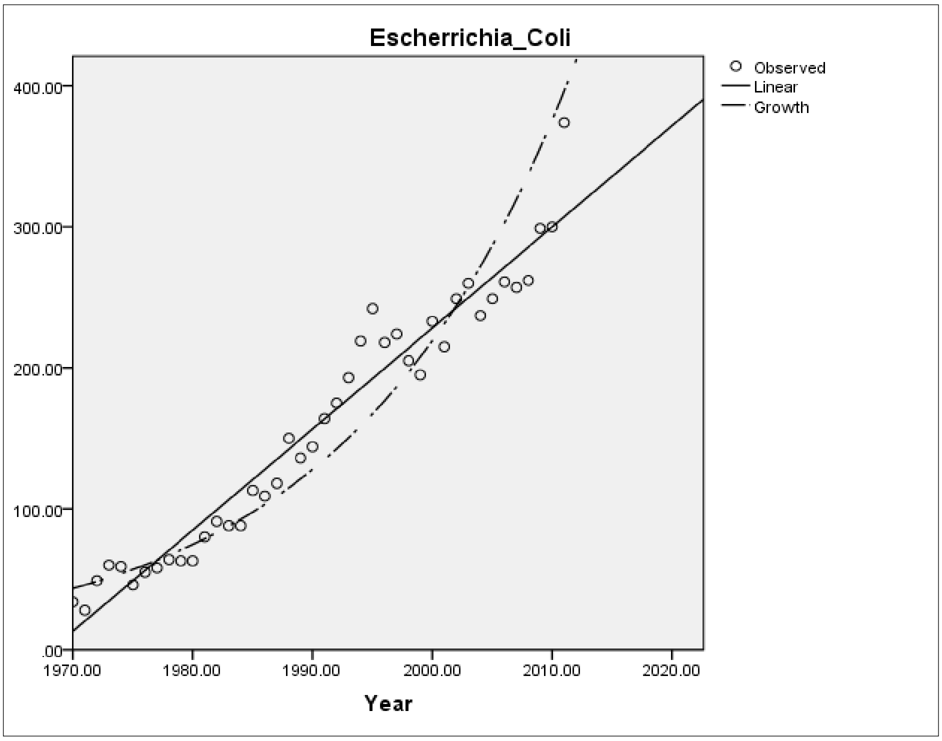
APPENDIX

CURVE FIT PER BACTERIUM BASED ON ESTIMATED RELATIONSHIP OF TABLE 6






Salmonella
Observed
Linear
Growth
50.00
40.00
30.00
20.00
10.00
1970.00
1980.00
1990.00
2000.00
2010.00
2020.00
Year


Escherrichia_Coli
Observed
Linear
Growth
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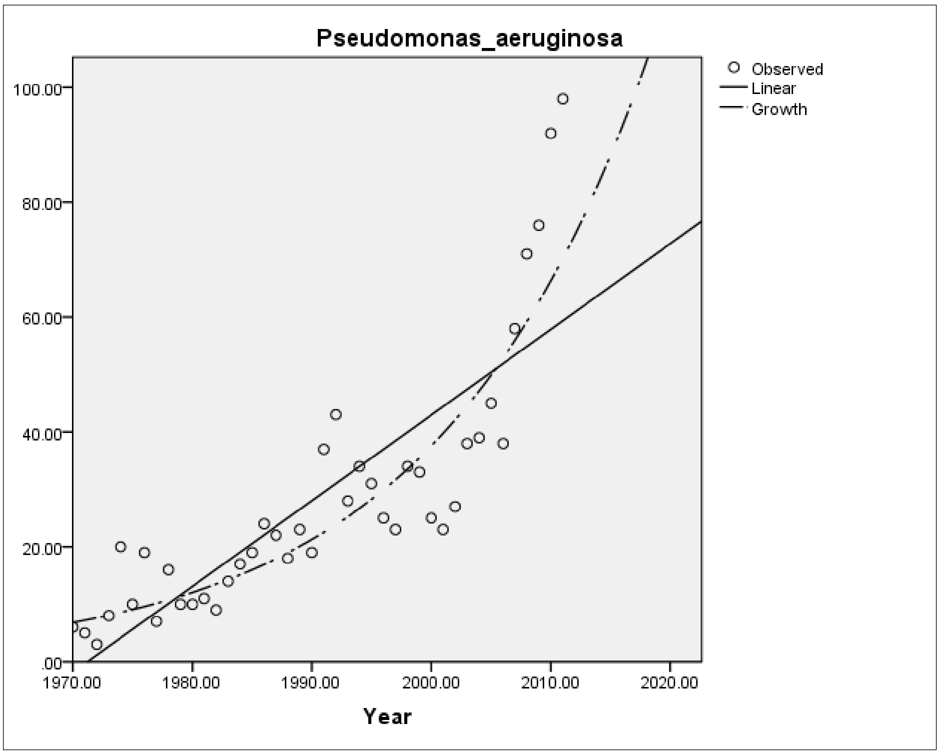
300.00
200.00
100.00
.00
1970.00
1980.00
1990.00
2000.00
2010.00
2020.00
Year



Pseudomonas_aeruginosa
Observed
Linear
Growth
100.00
80.00
60.00
40.00
20.00
.00
1970.00
1980.00
1990.00
2000.00
2010.00
2020.00
Year

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