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GREEN MOTION: a New and Easy to Use Green Chemistry Metric from Laboratories to Industry

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Green Chemistry metrics is a field of major importance. For the chemist who wants to demonstrate he has environmental friendly processes or to design processes in better compliance with the twelve principles of Green Chemistry, we designed a metric tool named GREEN MOTION™. It enables to assess the health, safety and Environment impacts of manufactured ingredients for the Flavour and Fragrance industry on a 0 to 100 scale. The safer and the less impactful the process, the higher the rating. In this article, the seven concepts funding GREEN MOTION™ are explained and data obtained from the assessment of all chemical products and natural extracts produced by MANE are illustrated with a focus on vanillyl ethyl ether synthesis. This article puts forward a novel approach designing a new green metric that enables to measure the overall safety of a product, its impact on the Environment and on the health of the people producing or using it. It offers a new continuous improvement tool which can be applied from Laboratories to chemical Industry.

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Introduction

In recent years, an increasing awareness of sustainability issues has led to a wide range of initiatives through the chemical industry. Closely linked to expectations from the end user, there is a trend for reducing carbon and water footprints, using renewable resources and minimising hazards.

In 1998, P. Anastas and J. Warner pioneered sustainability by introducing the Green Chemistry philosophy[1]. Based on twelve principles, it provides chemists with useful guidelines to design safer products for health and Environment. Since then, their publication remains THE reference of every paper or initiative around Green Chemistry. More and more articles are published about safer products, reactions or processes lowering the impact on the Environment, and that trend will only strengthen in the future. These very positive multiple initiatives will help the public to better understand Green Chemistry and its beneficial impact on the industry.

In a time of tough economic competition, and in a world where communication skills are more important than ever, manufacturers are facing the challenge of explaining their efforts to the public and their customers. Nowadays indeed, there is a blossom of sustainability indexes, with great variability, depending on the resources a company is ready to commit, or on its willingness to disclose information. Therefore, the question of green metrics is today more acute than ever. Most chemicals companies, from pharmaceutical industry to bulk chemistry and including MANE as a leader in the Flavour and Fragrance industry want to clearly communicate on their efforts and results to reduce Environmental impact. As a result, there is a need for a simple, easy to use, scientifically factual, reliable and generally accepted method that does not exist today. GREEN MOTION™ is an efficient tool that fits this purpose.

Green Chemistry and metrics

Although useful, the twelve principles of Green Chemistry are qualitative in nature and do not define clear metrics. Therefore, various simple metrics were developed founded on the twelve principles. The most famous and widely used one to measure the Environmental impact of a chemical process is the E-Factor, published by R. Sheldon[2]. The E-Factor, defined as the mass ratio of waste to desired product, includes reagents and solvent losses. It is both very informative and simple to calculate and on its successful track of diffusion, it was benchmarked through the chemical industry[3]. (Table 1) The reuse of E-Factor as a criterion for GREEN MOTION™ will be explained in the following parts.

Another metric, the Product Mass Intensity (PMI), can also be quoted. It has been chosen by the pharmaceutical industry to benchmark their process through the Green Chemistry Institute Pharmaceutical Roundtable. Defined as the ratio of the total mass used in process to the mass of desired product, the PMI can be directly related to the E-Factor: PMI = E-Factor + 1.[4]

However, there is lack of a reliable sustainable assessment tool. One difficulty is that applying only one or part of the twelve principles can become counterproductive and even lead to nonsense. Such a partial short term approach could damage the credibility of the company using it but also the confidence of the customers and/or the public towards the whole industry. Moreover, some of the principles may be contradictory with each other and it becomes difficult to know what type of actions to implement in order to find the optimal overall result. For example, a yield increase or a reduction of waste may entail higher energy consumption and this kind of conflicting choice is commonly faced by industrial chemists.

Most of the attempts to set green metrics are either too qualitative or require a large amount of information and thus much time and resources. Very few initiatives could be interesting for a chemical company willing to demonstrate its efforts to minimize its impact on the health and safety of its workers, its customers and the public, as well as its impact on the Environment.

Table 1 Typical E-factors for chemical industry sectors

Sector	Product Tonnage	E-Factor (kg waste per kg product)
Oil refining	10^6-10^8	<0.1
Bulk chemicals	10^4-10^6	<1 to 5
Fine chemicals	10^2-10^4	5 to > 50
Pharmaceuticals	10-10^2	25 to >100

Environmental-friendly processes are already in use at MANE

MANE's commitment to sustainable innovation is to develop chemical products and processes that are more respectful of the health, safety and Environment, from the laboratory to industrial scale. We already integrated many processes in optimized compliance with the twelve principles of Green Chemistry. We prefer producing ingredients from natural raw material extraction by applying the principles of Green Chemistry. Indeed, we are producing essentials oils by steam distillation using only water for the extraction and water is classified as the safest solvent. We are also extracting natural raw materials using organic solventsbut these solvents are chosen so as to give the best yield of extraction, reducing the amount of waste produced, and mild conditions of use – atmospheric pressure, low temperature. We are also doing extraction of natural raw materials using supercritical carbon dioxide as a solvent. Supercritical carbon dioxide is a safe and clean solvent. Even more, carbon dioxide is a waste from other industries: using it as a solvent just postpones the release of carbon dioxide into the atmosphere. The US FDA goes even further, considering that supercritical carbon dioxide is not a solvent.[5]However these different extraction methods are very high energy consuming processes with low yield, this is why we manage to recycle all water, all carbon dioxide, to select the solvents with the best recycling rate and to optimize extraction parameters to minimize water and energy consumption..

We privilege hemi-synthesis to obtain our molecules: using renewable sources as chemical substrate and trying to use their whole carbon skeleton in complete accordance with the Green Chemistry Philosophy.

We also use fermentation with microorganisms, and/or enzymatic reactions to transform natural substrates.

These are only selected examples among many more.

Our purpose is to optimize our processes according to Green Chemistry principles. Because of the lack of satisfactory tool in the industry, as explained previously, we decided to build our own methodology, for both promotion of our processes and continuous improvement regarding Green Chemistry. This tool is known as GREEN MOTION™.

GREEN MOTION™: designing a new tool

To design GREEN MOTION™, the challenges were numerous. First of all, the main driver was to set a metric that enables to rate a product and its specific process. Whatever the tool, it had to be quantitative and easy to understand. A rating between 0 and 100 was chosen, following the rule: the lower impact on the Environment, the higher the rating.

This rating has to integrate all twelve principles of Green Chemistry, which means including in the same tool all evaluations of health, safety, energy consumption or waste management for example. Also, it had to be compatible with any kind of chemical processes including synthesis, natural raw material extraction and biotransformation.

Some complex tools, such as Life Cycle Analysis, do take into account these many different parameters. However, this very resource and data intensive approach is not possible for each and every product and process. And there are many parts of the life cycle analysis which we cannot influence.

Furthermore, the assessment was to be clear, simple and relevant. Anybody that runs the same chemical reaction with the same manufacturing conditions would find the same GREEN MOTION™ rating.

Based on these objectives, GREEN MOTION™ was designed as a multi-criteria methodology working like an audit grid and based on the following approach:

We grouped the twelve principles of Green Chemistry into seven "fundamental concepts" (Fig. 1). These concepts are: Raw material, Solvent, Hazard and Toxicity of the Reagents, Reaction, Process, Hazard and Toxicity of the Final Product and Waste

Within each of these concepts, we looked for different criteria that would best assess the compliance with the principles of Green Chemistry: for example, yield from raw material origin or toxicity of the solvent. Each criterion was translated into simple questions for assessment purpose.

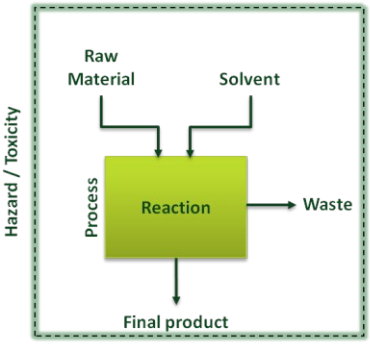

Fig. 1 The twelve principles of Green Chemistry grouped into seven fundamental concepts

The assessment begins with an amount of one hundred points for each answered question, an amount of penalty points would be subtracted if any negative impact is found. Simple answers consist of either "Yes" or "No", or multiple choice, or a number. For one given criterion, the higher the impact on health, safety, or the Environment, the higher the number of penalty points. Note that for one given criterion, the total assessment could theoretically end up with a negative score.

Afterwards, a set of 81 products manufactured by MANE including synthetic molecules, natural extracts and products derived from microbiological process was selected to design GREEN MOTION™. The number of penalty points assigned to each criterion was defined according to the following rules: the penalty points across the seven concepts must be balanced, any process improvement must be measurable and the overall rating range from 0 to 100 must be used. The Fig. 2 illustrated the final set of GREEN MOTION™ ratings for selected products after balancing all penalty points.

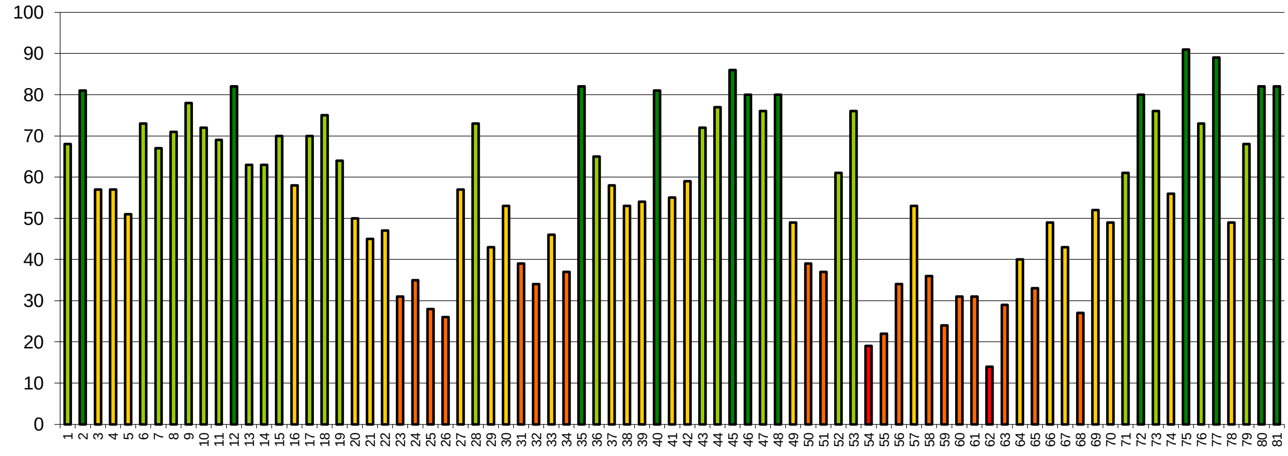

Fig. 2 Set of 81 products slected to design GREEN MOTION™.

Seven fundamental concepts

The following part describes the criteria within the 7 fundamental concepts of GREEN MOTION™ and is recapped inTable 7.

Raw material origin

A natural raw material is a raw material of vegetable, animal or microbiological origin, including the products derived from this material by enzymatic processes or by traditional procedures of preparation (For example : heating, roasting or fermentation).[6]

According to the principles of Green Chemistry, using natural raw materials will not be penalized by GREEN MOTION™ contrary to non-renewable ones (Table 2).

To complement the criterion regarding the use of natural raw materials, another criterion on the naturalness of the process was added. Based on EFFA's definition, a natural process is a physical method which does not intentionally modify the chemical nature of the components, for example: microbiological process, extraction or distillation.[7]Similarly, natural processes will be privileged over chemical processes and penalty points will be given to non-natural processes.

Table 2 Raw material origin categories

Category	Penalties
Synthetic raw materials	10
Raw materials from hemisynthesis	5
Natural raw materials	0

Solvents selection

Two main ideas of Green Chemistry can be found in the section dedicated to solvent: the estimated impact of the solvent on human health, safety and Environment, and the promotion of eco-friendly solvents such as water or supercritical carbon dioxide. Based on these two notions, the solvents have been classified into 5 categories with some penalty points assigned (Table 3). A completely solvent-free process being considered as the best option, even the use of water will add penalty points to the final rating.

Table 3 Solvent categories

Category	Examples	Penalties
CMR and toxic solvent	Methanol, Methylene Chloride, Benzene...	10
Petrochemical solvent	Toluene, Hexane, Cyclohexane...	5
Supercritical fluid	Carbon dioxide	2
Ethanol		2
Water		1
No solvent used		0

Using raw materials and solvents that show little or no toxicity to human health and the Environment

To identify the hazard and toxicity of a material, communication items are proposed on labels and safety data sheets by the "Globally Harmonized System of Classification and Labelling of Chemicals" (GHS). The GHS makes sure that information about the chemicals hazards and toxicity are available to improve the protection of human health and the Environment during the handling, transportation and use of chemicals.

The hazard and toxicity section of GREEN MOTION™ is based on the GHS pictograms: inspired by the hierarchical organization of hazards defined by INERIS[8], some penalty points are attributed to each pictogram according to its level of hazard (Table 4). For example, if one reagent is corrosive, 2 penalty points will be given.

Table 4 GHS Pictograms hierarchy

Pictogram	Penalties
	4
	3
	3
	2
	2
	1
	1
	1

Reaction efficiency

Though a reaction process can be optimized by reducing the number of steps, reducing reagents uses, or using catalysts, it is also important to keep in mind that the yield remains one of the best indicators of the efficiency of a reaction or extraction process.

Another criterion is atom economy. To simplify the atom economy defined by Trost[9] and the carbon efficiency defined by Curzons et al[10], we developed our own atom economy approach based on the carbon economy and the protection/deprotection criterion. (Table 5)

The carbon economy is calculated for each step of any chemical synthesis. It is defined by the ratio of the number of carbon atoms of the finished product to the number of carbon atoms of all C-containing reagents involved. For example, a reduction step leading to the loss of carbon atoms will be penalized contrary to a rearrangement or addition step in which the total carbon atoms engaged will be kept. For example, carbon economy calculation can be done on the synthesis from Fig. 3with R replaced by a propyl group and R' by a methyl group. The Table 5compares our approach with the atom economy defined by Trost.

Some molecules can be used to improve reaction selectivity and the use of a functional group for protection/deprotection is transparent with our approach. That is why the number of protection/deprotection steps is taken into account by GREEN MOTION™.

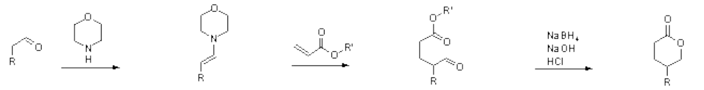

Fig. 3 Example of a synthesis for carbon economy calculation

Table 5 Comparison between GREEN MOTION™ Atom Economy and Trost Atom Economy

	1. Activation	2. Addition	3. Reduction	Total
GREEN MOTION™ Carbon Economy	$\frac{9}{4+5}=1$	$\frac{9}{4+9}=0{,}69$	$\frac{8}{9}=0{,}89$	0.61
Trost Atom Economy	$\frac{155}{87+86}=0{,}90$	$\frac{172}{155+86}=0{,}71$	$\frac{142}{172}=0{,}83$	0.53

The Trost definition is more accurate, but GREEN MOTION™ carbon economy follows the same trend and is simpler. Moreover, the other atoms are taken into account with the E factor.

Process efficiency

The ideal situation would be a fast process at ambient temperature and atmospheric pressure. Most of the time however, it is necessary to change temperature and/or pressure conditions so as to improve the reaction, thus affecting energy consumption.

Contrary to the energy study of the complex Life Cycle Analysis methodology, we decided to focus on the most energy consuming elements: heating, cooling and varying pressure.. For example, we will not try to calculate accurately the quantity of heating energy required throughout the process. Instead, GREEN MOTION™ focuses on rating the heating process and the heating time. The more energy consuming the heating process is, the more it will be penalized (Table 6). For example, steam will be preferred to gas heating because it is safer and more efficient.

The same approach is used for cooling, and pressure variation.

Additional unitary process with high energy consumption, such as crystallization, will also score penalty points.

Table 6 Penalty points attributed for different heating processes

Gas	6	7	8	9	10	11	12	13
Electrical resistance	5	6	7	8	9	10	11	12
Oil	4	5	6	7	8	9	10	11
Steam up to 15b	4	5	6	7	8	9	10	11
Steam up to 6b	3	4	5	6	7	8	9	10
Steam up to 3b	2	3	4	5	6	7	8	9
Steam	1	2	3	4	5	6	7	8
Ambient Temperature	0	1	2	3	4	5	6	7
	12h	24h	48h	96h	144h	192h	240h	288h

Designing products with respect of the Environment and no impact on human health and safety

Similarly to reagents and solvents, GREEN MOTION™ is based on GHS pictograms to assess the final product's hazard and toxicity. This section focuses particularly on health impact associated with the skull and crossbones pictogram and the Environmental impact (persistence, bioaccumulation and toxicity) related to the "dead fish" Environment pictogram.

Waste reduction

The E-Factor is a useful indicator to measure the amount of waste generated by a process and attempt to optimize the reaction. It is probably the most widely used across green metrics in the industry and is defined as the weight ratio of the waste generated to finished product obtained. We decided not to include water into the amount of waste generated and E-Factor was preferred to PMI because it fits better with an objective of zero penalty point for an E-Factor equal to zero.

The E-Factor is included into our GREEN MOTION™ assessment tool.

Table 7 Green metrics selected in GREEN MOTION™

Concept	Major criterion		Unit
Raw material	Raw material origin		Category
	Process naturalness		Yes/No
Solvents	Solvent category		Category
Hazard and toxicity of the reagents	GHS Pictogram		Pictogram
Reaction	Mass yield		%
	Number of steps		Number
	Number of solvents		Number
	Carbon economy	$\frac{\text{Number of carbons of product}}{\text{Number of carbon of reactants}}$	%
	Number of protection/deprotection step		Number
	Overall processing time		Hour
Process	Most consuming heating process		Category
	Most consuming cooling process		Category
	Vacuum		Category
	Pressure		Category
Hazard and toxicity of the final product	GHS Pictogram		Pictogram
Waste	E-Factor	$\frac{\text{Mass waste (kg)}}{\text{Mass desired product (kg)}}$	kg/kg

GREEN MOTION™ assessment of one thousand molecules and extracts

Early in 2012, the tool was finalised and all products produced by MANE were eventually rated using GREEN MOTION™. Fig. 4 shows the distribution of ratings for more than one thousand products. This work was carried out in twelve months, which is a remarkably short time given the volume of data collected and gives also a good idea of how efficient it is.

In order to measure how MANE progresses in developing and promoting safer products and processes having less impact, and to establish a baseline for progress plans and external benchmark, we arbitrarily defined a "green limit": the GREEN MOTION™ value of **50**. 75% of MANE products are above this limit (Fig. 4).

GREEN MOTION™ is now operational at MANE: each new product coming from our research laboratories which is then scaled up and transferred into production is rated by this methodology.

This rating was also fully integrated in our in-house formulation tool, which means that GREEN MOTION™ rating is an additional criterion for the selection of fragrance or flavour ingredients, in addition to price and performance.

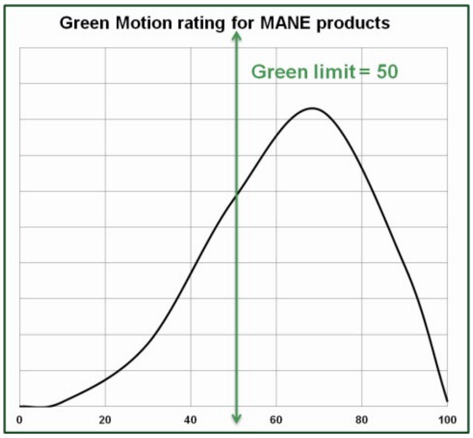

Fig. 4 GREEN MOTION™ rating for MANE products

GREEN MOTION™ usage as a continuous improvement tool

Once a process/product couple has been assessed, it obtains a GREEN MOTION™ rating. This rating is the reference point from which we will monitor and quantify any process changes to improve the overall Environmental impact of its production. Since 2012, all improvements made on a process have been rated by GREEN MOTION™.

As a case study, we present the example of the production of Vanillyl Ethyl Ether (VEE).

MANE produces VEE: it is a molecule used in the flavour industry for its vanilla flavour and its specific warming effect. Its industrial synthesis (described in Fig. 5) starts from vanillin. The first step is a reduction of the aldehyde into an alcohol and the second step is an etherification.

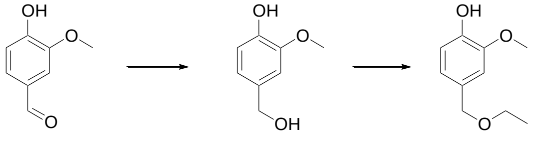

Fig. 5 Vanillyl ethyl ether synthesis

The synthesis was industrialized in 1997 and since then, many improvements, shown in Table 8, have been brought to the process.

Table 8 Reaction optimization of VEE

	Solvent	Solvent toxicity	Yield	Number of steps	Global process length	E-Factor	GREEN MOTION™ rating
1997	1,2-Dichloroethane	Can cause cancer	50%	4	356h	2,3	23
2002	Dichloromethane	May cause cancer	51%	4	356h	2,2	24
2012	Toluene	Not carcinogenic	45%	3	182h	1,2	37

Through these improvements, the GREEN MOTION™ rating of VEE has increased from 23 to 37. Fig. 6 represents the GREEN MOTION™ ratings of VEE regarding the 7 fundamental concepts. The wider the area, the higher the GREEN MOTION™ rating.

Focus on each concept

Raw material. There is no visible improvement from an Environmental point of view.

Solvents. The major improvements for the synthesis of VEE were achieved by choosing the best solvent considering its efficiency, toxicity and recycling rate. The first solvent used was 1,2-dichloroethane : it is very efficient but carcinogenic. It was therefore replaced by dichloromethane, for a similar efficiency, but suspected of causing cancer. The best choice was eventually toluene.

Hazard and toxicity of the reagents. No significant improvements are observed.

Reaction. The replacement of the solvent by toluene decreased the yield by 6%, leading to a lower GREEN MOTION™ rating. However, this drop was compensated by some other improvements: one purification step was no longer necessary and the overall processing time was divided by 2.

Process. Higher rating is linked to continuous improvement.

Hazard and toxicity of the product. No difference the final product being identical.

Waste. The E-Factor was reduced from 2.3 to 1.2.

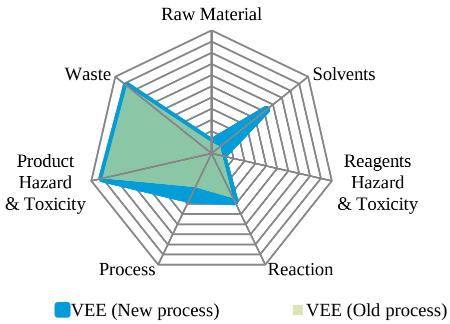

Fig. 6 GREEN MOTION™ assessment of Vanillyl Ethyl Ether process improvements

Conclusion

GREEN MOTION™ is a simple and quantitative method. The necessary information for a product and the process to make it being available, a full assessment can be conducted in only half an hour, which is of unequalled efficiency. It is adapted to all kind of products and processes, from natural extractions to multi steps chemical synthesis. Nevertheless it shows some limitations and does not pretend to be the answer for everybody's need. At first GREEN MOTION™ is a gate-to-gate analysis, and if taking into account the origin of raw materials, it does not look at their manufacturing processes. Secondly, the penalty points were chosen by the authors of the method and are arbitrary by definition. They have been carefully cross checked and are well suited for the evaluation of Fragrance and Flavour ingredients.

Having set this frame, GREEN MOTION™ is to our knowledge the only method that allows an assessment of the compliance to the twelve principles of Green Chemistry. It is a very useful tool for process development, from laboratories down to industrial workshops, for continuous improvement, and it also gives an additional selection criterion for the end user, sales people for example, or perfumers and flavourists in our industry. More than one thousand ingredients have been rated, demonstrating the robustness of the method, and building a useful database for further benchmarking.

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GREEN MOTION^{TM} by MANE is a novel approach designing a new green metric that enables to measure the overall safety of a product, its impact on the Environment and on the health of the people producing or using it.