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An aggregate fuzzy hazardous index for composite wastes

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Abstract

In this paper, a fuzzy waste index for evaluating the hazard posed by composite wastes generated from industrial processes is proposed. Within this methodology, a fuzzy index as a measure of hazardousness of a given composite waste is derived from the crisp inputs of its component's flammability, corrosivity, toxicity and reactivity attributes based on the National Fire Protection Association (NFPA) hazard rankings. The novelty of this work lies in establishing an integrated fuzzy hazardous waste index (FHWI) which provides a single-value representing the hazard ranking of a composite waste. This is contrary to current techniques which do not provide a final aggregated hazard index. The efficacy of the new proposed approach is illustrated through several worked examples. The results demonstrate that the fuzzy algorithm can be useful in aiding policy and decision-makers in conducting comprehensive initial evaluation of the status of waste hazardous status without the need for costly laboratory experiments. As such, the approach offers a robust and transparent decision-making methodology.

Keywords: Hazardous waste; Fuzzy hazardous waste index; Uncertainty evaluation; Fuzzy logic

1. Introduction

In the 21st century, globalization is viewed as means of meeting the exponentially growing needs of the world population in terms of improving people's lifestyles, and as an avenue of fulfilling growing individual consumption through the provision of goods and services. Moreover, this phenomenon has triggered rapid expansion of industrialization and urbanization, intensive agriculture and rigorous exploitation of natural resources [1]. Unfortunately, such developments have been accompanied by a large negative footprint, resulting in damage to the ecosystem, generation of large quantities of wastes (ranging from benign to highly hazardous), environmental pollution (air, water and land), extinction of certain species, global climatic change, energy crises, loss of agricultural land through deforestation owing to soil erosion and urbanization, increased mortality and morbidity [2–8].

Undeniably, mankind lifestyle has considerably improved since the turn of the 19th century owing to innovative technological advancements. However, these comforts have been accompanied by an enormous generation of hazardous wastes. One of the greatest challenges in dealing with the hazardous wastes is to classify them in terms of their toxicity, flammability, corrosivity and reactivity. The challenge is aggravated by the high risks involved, lack of sufficient time and huge financial costs required to study a large range of different wastes. Likewise, there is at present no systematic methodology to integrate all attributes of hazardous wastes into a single measure of the hazardousness of a composite waste.

In the past, hazard ranking of a given material has been expressed as indexes based on Boolean mathematical methodologies. The idea has been to provide decision tools to the industrialists, experts, transporters and policy and decision-makers in arriving at appropriate decisions in the process of dealing with hazardous wastes. These decision models have been designed to act as a good guide to personnel involved in a variety of activities such as producing, collecting, packaging, storing, transporting, recycling, treating, disposing, as well as handling of emergencies and antidotes [9–15]. The basic premise of this classical approach is the assumption that, hazardous waste attributes such as flammability, reactivity, and so forth, can be rated and ranked in finite classes.

However, in certain cases these classical methods have lead to inconsistent results, since unavailable data were usually esti-

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mated according to averaged values or using values of similar elements which may not be a true reflection of the substances in the composite hazardous wastes. Furthermore, these methodologies sometimes introduce excessive accuracy in their calculations, which may be unwarranted by the uncertainty of the available data.

Therefore, there is still a need for a systematic and easy-to-use tool that can be used to rank the hazardousness of a composite waste by taking into account all the waste characteristics. The current authors attempt to fill this gap by proposing an aggregated FHWI based on fuzzy logic [16,17]. The merit of this approach is that it allows the use of both qualitative and quantitative variables, which do not require high computing power to establish the relationship between the inputs and outputs. As a result, the fuzzy logic simplifies decision making in this domain which is characterised by uncertainty, imprecision and subjectivity. The model is based on the idea of simulating the way of reasoning of an expert ranking the hazardousness of a given composite waste. As a way of illustrating the applicability of the proposed methodology, several practical examples, including two from the literature regarding the evaluation of the hazardousness of composite wastes will be presented and discussed.

2. Background

2.1. Definition of hazardous wastes

Hazardous wastes are viewed as wastes that may cause or significantly contribute to extensive damage to both humans and the environment when poorly handled. Owing to their ability to cause widely varying negative impacts, many countries (e.g. South Africa [18], USA [19]) have adopted different regulatory frameworks. In this work, the definition by the United Nations Environmental Programme (UNEP) is used. In UNEP hazardous waste are non-radioactive wastes which, by reason of their chemical reactivity or toxic, explosive, corrosive or other characteristics, cause danger or are likely to cause danger to human health or environment, whether alone or when in contact with other wastes.

Within the broad framework of the UNEP definition as well as the Resource Conservation and Recovery Act (RCRA) of the USA [19], a waste can be considered to be hazardous if it exhibits one or more of the following attributes:

- *Flammability*: Refers to wastes capable of creating fires during routine management. This property depends on the flash point of the material. Examples include liquids and ignitable gases that catch fire readily, substances that are friction sensitive or that can cause fire through adsorption of moisture.
- *Reactivity*: It is the ability of a material to react both with itself and other materials under normal conditions. This is because of the material's instability and the tendency to react vigorously with water, or air at ambient conditions, or sensitivity to shock, or heat, resulting to the creation of explosions, runaway reactions or toxic fumes.
- *Toxicity*: It is a measure of the ability of a material to pose substantial hazard to human health or the environment. Organisms are exposed to toxic chemicals through inhalation, ingestion, or skin absorption pathways. Exposure of living organisms to toxic wastes can cause direct and indirect impacts which can broadly be categorized as carcinogenic, mutagenic and teratogenic effects, reproductive system damage, respiratory effects and central nervous system effects, among other.
- *Corrosivity*: Refers to the capability of a material to corrode metals owing to the strength of its acidity or alkalinity. Such wastes require special handling and containers (e.g. drums, tankers and barrels) to ensure they do not dissolve toxic contaminants.

2.2. Hazardous waste generation

Hazardous wastes are generated from wide ranging sources such as the process industries, small and medium businesses, households, research and testing laboratories, agricultural industry and, health related services and industries. The process industries are the largest producers of hazardous wastes. The quantities of hazardous wastes generated vary from one industry to the other as do their impacts on humans and the environment.

Considerable work has been done to quantify the generation of hazardous wastes. Some of the global statistics can be found in references [20–23]. Nevertheless, a peculiar phenomenon of hazardous wastes inventory worldwide is that databases in OECD countries are regularly updated, owing to a well developed and comprehensive legislative framework. On the contrary, such statistics are very scarce in non-OECD states, although large heavy industrial generators of hazardous wastes are currently relocating into these countries, owing to their weak or non-existing regulatory regimes [8,24].

Moreover, the quantification of the hazardous wastes generated globally has been recognized as a great challenge owing to non-standardized techniques of data reporting and different manner in which they are defined in different countries. For instance, clear disparities can be noted on the figures published by Hsing et al. [23] for global generation and those for USA [25,26]. The discrepancies of the reported statistics can be attributed to heterogeneity of influencing variables, such as source elimination or reduction, process modification through material substitution, housekeeping principles adopted, degree of reuse and recycling, production management style, raw material alteration and product substitution.

2.3. Hazard indices

As a way of dealing with the challenges of safety, chemical process loss prevention and risk management during industrial processes, transportation and handling of hazardous materials, a wide variety of hazard indices have been proposed and developed. A good summary of these indices has recently been presented by Khan et al. [27,28], and therefore we will only review those of direct relevance to this work. In this section, a brief review of the hazard indices that bear close relevance to the present work is presented.

The first attempt to derive an index (HWI) for a hazardous waste was proposed and developed by Gupta and Babu [9]. Its purpose was to facilitate decision-making during handling, transporting, treating and disposal of or recycling hazardous wastes. However, in the development of this index no attempt was made to integrate the indices related to flammability, corrosivity, toxicity and reactivity into a single-value output representing the overall hazard ranking of the composite waste.

Taylor et al. [10] introduced a technique to determine the toxicity hazard potential of a single chemical. As a result the developed toxicity index is inadequate when one considers the evaluation of toxicity of a composite hazardous waste. This is because it fails to take into account other hazard causing attributes, such as corrosivity and so forth. Moreover, a single chemical in all likelihood can be a useful raw material in another process.

Recently, Rajeshwar et al. [11] presented a method using NFPA hazard rankings for flammability, corrosivity, reactivity and toxicity to calculate risk indices of chemicals they pose during the transportation of hazardous wastes. Among the factors incorporated in this method were the quantity of material moving, the distance between the point of release and human populations in the proximity, rate of dispersion and the probability of an accident occurring. As the factors considered in their study were related to transportation, the derived index has limited applicability in hazard ranking of chemicals in other processes, such as disposal, production and recycling.

Kraslawski and Nyström [29] proposed and developed a hierarchical fuzzy index for the purpose of comparing product and process toxicity related to different design alternatives. Therefore, introducing a fuzzy-based index made it easy to compare conclusively the impact of various designs on the levels of toxicity hazard generated using quantitative-based computing techniques. However, the proposed fuzzy index is only applicable at the process and product design stage and may not be suitable for assessing hazard levels of wastes during handling, transportation and disposal processes. In that way, the fuzzy index fails to provide a comprehensive method of assessing all the hazardousness that may be present in a given composite waste.

3. Fuzzy logic approach

3.1. Basics of fuzzy logic

Fuzzy logic is rooted in the concept of fuzzy sets initiated by Zadeh in 1965 [16]. It facilitates the simulation of reasoning in human expert(s) in a domain characterised by vagueness, uncertainty and subjectivity. Fuzzy set theory, unlike the two-valued logic that restricts a member to belong to a mutually exclusive set, allows an element to reside partially or totally in several sets at the same time. In a fuzzy system the variables are regarded as linguistic variables, owing to the fuzzy logic ability to 'compute with words'. A linguistic variable here refers to a variable whose value is a fuzzy number or is a variable defined in linguistic terms [30]. Each linguistic value, LV, is represented by a fuzzy set using a membership function $\mu_{\mathrm{LV}}(x)$.

The membership function associates with each crisp input, say X_{A}, a number, $\mu_{\mathrm{LV}}(\mathrm{x_A})$, in the range [0,1] which represents

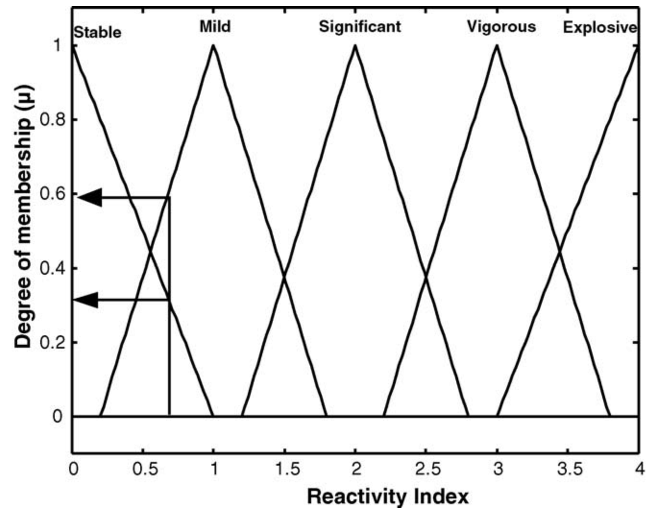

Fig. 1. Membership functions of the set of hazard rankings associated with hazardous composite waste reactivity attribute.

the grade of membership of X_{A} in LV or equivalently, the truth value of proposition 'crisp value A is LV'. The overlapping of the membership functions allows an element to belong to more than one set at the same time, and the degree of membership into each set is an indication of how much the element belongs to that particular fuzzy set. For example, if the computed reactivity index of the composite hazardous waste is 0.7, then according to Fig. 1, the membership functions $\mu_R(x_i)$ generated are $\mu_1 = 0.32$ in the fuzzy set labelled *stable*, $\mu_2 = 0.60$ in the set labelled *mild*, and in the rest of sets $\mu_3 = \mu_4 = \mu_5 = 0$ for the sets *significant*, *vigorous* and *explosive*, respectively. In this study both triangular and trapezoidal functions were used to represent variables, while the knowledge was encoded in the knowledge base using the IF-THEN rules.

3.2. Fuzzy inferencing

In order to simplify and minimize computation time, a modular system development approach was adopted, which resulted in the construction of several sets of IF-THEN rules. In general, a fuzzy logic system is comprised of a fuzzifier, fuzzy rule base, fuzzy inference engine and a defuzzifier as presented in Fig. 2. The fuzzifier is responsible for converting the crisp input data into a linguistic value acceptable for computing the system output with the aid of membership functions. The fuzzy rule base contains a set of IF-THEN rules that defines the relationship between the assigned or measured input variables to the anticipated system output (hazardous of the waste under consideration). The rule base is supported by a knowledge base which defines the membership functions used in the generation of the IF-THEN rules.

The core of the decision-making algorithm in a fuzzy logic system is the inference engine. It is instrumental in the derivation of an aggregated output from a particular module from the IF-THEN rules in its rule base. In practice, many fuzzy inferencing methods have been developed, with the so-called *max-min* and *max-dot* or *max-prod* [30] being the most popular. In this study, the *max-min* fuzzy inferencing algorithm proposed by Mamdani

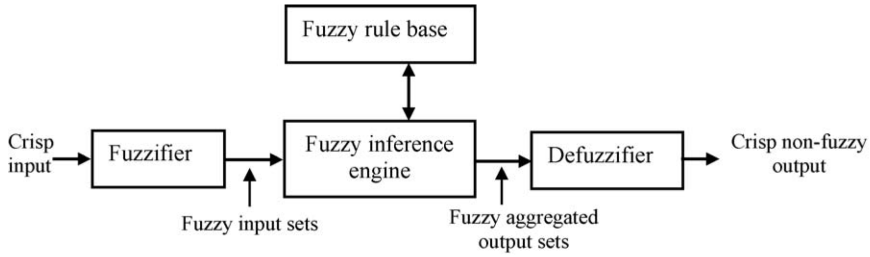

Fig. 2. The fundamental configuration of the fuzzy reasoning algorithm.

and Assilian [31] was used, which involves the clipping of the truth value of the fuzzy output variables, such that the area under the clip line determines the outcome of the rule.

Finally, the defuzzifier converts the fuzzy aggregate membership grades generated from the inference engine into a non-fuzzy output value. There are again various approaches to defuzzification [32,33]. The most common of these is the centroid method [34], which was also used in this paper, because it is sensitive to the contribution of each activated rule, as opposed to other methods which have a strong bias towards rules with higher truth values or firing strengths.

4. Methodology for evaluating aggregate FHWI

The proposed methodology follows a step-by-step procedure involving fuzzy concepts and hierarchical analysis to determine the aggregate FHWI of a composite waste. As described in Section 2, hazard ranking of a waste is a function of its flammability, reactivity, corrosivity and toxicity. Previously, methodologies based on Boolean mathematics were developed to compute the hazard ratings of materials for one or more of these attributes [10,13,27–29]. As a result, the indices determined from such approaches assumed that each sub-range was bounded by sharp boundaries and that a specific characteristic could only belong to one set at a time. However, in this study the fuzzy methodology is adopted to aggregate the individual indices into a composite hazardous waste index, taking into account the multiplicity and ambiguity of the evaluation criteria in the aggregation process to ensure a more reliable decision.

The assessment framework is comprised of three parts. The first part determines the fuzzy index of each attribute. These calculations were based on the use of crisp or non-fuzzy numbers as inputs for each attribute based on the waste's constituent component values, obtained directly from previous studies or measurement of the waste pH. For instance, flammability and reactivity hazard indices were obtained from reference [13], while corrosivity is expressed in terms of the pH of the composite waste. Ranking corrosivity on the basis of pH value as opposed to the composite waste's capability to corrode steel was adopted, because the emphasis of this work is biased towards safeguarding possible damage on humans and ecological systems. In that regard, pH then served as crisp input into the corrosivity knowledge rule base to compute the corresponding linguistic corrosivity value.

The second part of the framework was based on aggregation of first-level fuzzy hazard indices of flammability and reactivity to generate the flammability–reactivity fuzzy hazard rating, similar to the material factor (MF) [13,35]. The third level of the aggregation process focused on combining the fuzzy flammability–reactivity hazard index derived in the second level and the first-level fuzzy hazard indexes of corrosivity and toxicity. An illustration of hierarchical model structure for determining the aggregative FHWI is depicted in Fig. 3.

The fuzzy model reported in this paper uses the crisp inputs of the hazard rankings reported in literatures [13,35,36] specifically for the case of flammability, reactivity and toxicity attributes. In addition, the weighted average hazard ranking for the flammability, reactivity and toxicity of a composite waste

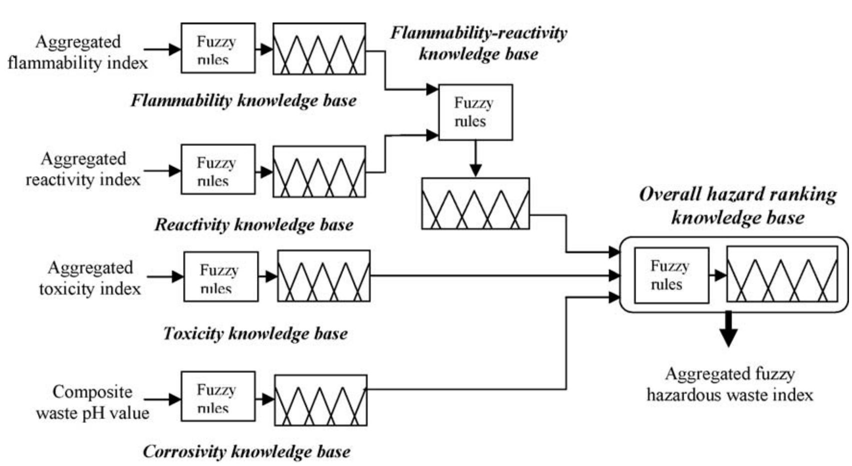

Fig. 3. The hierarchical structure of aggregative FHWI model.

were computed following the procedure described by Gupta and Babu [9]. It should be noted that the weighted average hazard rating method was used in this study, because the overall ranking for each attribute was expected to be proportional to the numerical value of the individual elements constituting the hazardous waste.

However, contrary to the procedure used by Gupta and Babu [9] where the overall composite waste hazard ranking calculated for a specific attribute was rounded to ensure that the final value fitted into an exact defined classical set, in this study, the computed values were used directly as crisp inputs into the respective fuzzy models to compute the linguistic values of each attribute. A stepwise description of the adopted approach is as follows:

I. Identifying the composition of the waste, and particularly analysing the quantities of each constituent component present.
II. Use of the reactivity, flammability and toxicity hazard indices for each constituent component in the composite waste reported in the literature. Toxicity hazard ranking should be expressed in TLV values.
III. Use of the results derived in steps I and II, to compute the weighted average flammability, reactivity and toxicity hazard rankings of the composite hazardous waste.
IV. Measuring of the pH of the composite waste.
V. Using the results of steps III and IV to compute the fuzzy hazard rankings of flammability, reactivity, toxicity and corrosivity of the composite waste.
VI. Aggregating the fuzzy outputs for flammability and reactivity obtained in step V, to calculate the flammability–reactivity aggregate hazard ranking.
VII. Aggregating the fuzzy rankings of toxicity and corrosivity obtained in step V and the fuzzy model outputs of step VI to obtain the final hazard ranking of the composite waste.
VIII. Matching of the fuzzy hazard waste ranking with an appropriate qualitative linguistic hazard ranking level.

5. Determination of composite waste hazard rankings

In this section we calculate the cumulative hazard ranking of the waste as a function of the constituent components ratings. The idea is to derive the cumulative flammability, toxicity and reactivity of the composite waste using first-level values based on constituent components hazard rankings obtained from the open literature. All the hazard rankings used in this work were obtained from references [13,35–37].

Many methods can be used to aggregate the hazard ranking for each hazardous waste attribute, such as the arithmetic mean, median, maximum, minimum, multiplication and mixed operators. However, in this study the arithmetic mean operation is used because it is the most popular and realistic. Moreover, it allows the effect of each waste constituent component to be proportionally reflected in the final composite waste hazard ranking, and therefore offers a more representative outcome.

5.1. Flammability and reactivity hazard ranking

The NFPA [35] developed hazard ratings for flammability and reactivity on the basis of the material's susceptibility to burning and ability to release energy in accordance to the set of conditions prevailing, respectively. To represent the hazard rankings for flammability and reactivity attributes, each attribute was subjectively evaluated and assigned indices ratings ranging from 0 to 4 at interval steps of 1. The higher the score ranking, the higher the risk a given composite waste poses to both humans and the environment. For instance, a material assigned a flammability value of 4 is presumed to be highly flammable, while a material with a value of 0 is assumed to be inert.

To define the flammability of the composite waste, an aggregated average value is obtained using an equation of the form

$$I_{\mathrm{Fcw}} = \sum_{i=1}^{n} y_i \mathrm{NF}_i \qquad (1)$$

where y_i is the mass fraction of component i in the composite waste expressed in the range 0–1; n the total number of components constituting the composite waste; NF_i the flammability index of component i and I_{Fcw} is the weighted flammability of the composite waste. Note that the flammability hazard rating (I_{Fcw}) owing to the composite waste takes any value between 0 and 4.

Similarly, the aggregated reactivity value of the composite waste is defined as:

$$I_{\mathrm{Rcw}} = \sum_{i=1}^{n} y_i \mathrm{NR}_i \qquad (2)$$

where NR_i is the reactivity index of component i and I_{Rcw} the weighted reactivity of the composite waste. The reactivity hazard rating due to composite waste reactivity (I_{Rcw}) takes any value between 0 and 4.

5.2. Toxicity hazard ranking

As is the case with flammability and reactivity, Dow [13] and NFPA [35] provide the degrees of health hazard ranking for a given element according to the probable severity of the effect(s) it may cause on the personnel exposed to toxic materials in processing plants during normal working conditions. The health hazard ranking assigned to any given element ranges between 0 and 4 in steps of 1. However, in this study toxicity value is expressed using the threshold limit values (TLVs) system [36]. This is because the TLVs system has relevance to a wide range of users such as decision and policy makers, personnel dealing with handling and transportation of hazardous wastes, and the public at large unlike the health hazard rankings which only target personnel working in processing plants. In this system, lower TLVs imply that the element is highly toxic, while higher values signify a less toxic hazard ranking. Thus, the aggregated weighted toxicity hazard index T of a composite waste is expressed as:

$$T = \sum_{i=1}^{n} \left(\frac{y_i}{\mathrm{TLV}_i} \right) \times 100 \qquad (3)$$

where TLV_i is the threshold limit value for component i.

5.3. Corrosivity hazard ranking

The corrosivity hazard ranking index is for the entire composite waste and not a function of the cumulative aggregate of the constituent components. In practice, corrosivity can be expressed in two ways depending on the intended application. On the one hand, it is expressed in terms of the material's potential to cause a hazard impact (erosion) on the construction material of the container holding the waste. Thus, corrosivity is measured as a function of length per year, and expressed in units such as mm/year.

On the other hand, corrosion is considered on the basis of the waste's ability to cause harm when in contact with living tissues. In this case, the corrosivity potential indicator is the pH [37] of the hazardous waste. Wastes having very high or very low pH values are classified as very corrosive, while those with values ranging between 6 and 8 are presumed to be non-corrosive. This is because wastes with low (pH 2) or high (pH 12) pH values have the potential to react dangerously with other materials or tissues resulting to corrosive effects. In this study, the pH scale is adopted in calculating the corrosivity index of the hazardous waste. Moreover, the pH of a hazardous waste can be easily measured, and is well understood by personnel and experts from a wide range of backgrounds. The corrosivity fuzzy module input, pH′, is computed using the expression

$$\mathrm{pH}' = \mathrm{abs}(\mathrm{pH} - 7) \qquad (4)$$

where pH′ is the absolute value of the difference between a given pH and 7.

6. Fuzzy quantification of hazard ranking

In this section, the fuzzy mechanism of evaluating the overall hazard rating of a given hazardous waste is described. The model was developed based on the premise that hazard rankings used by experts to denote any hazardous attribute are subjective, contains non-probabilistic uncertainty and in practice represents a qualitative linguistic class. In that sense the crisp numbers assigned by the experts can be used as fuzzy input numbers to determine the linguistic class of the 'hazardousness' which provides a true reflection of real operational conditions.

As the hazard rating values associated with a given level of hazardous attribute are qualitative in nature, we propose a more consistent framework in the ranking description. The proposed methodology is based on fuzzy logic, which has the merit of allowing the smooth transition of the measure of hazardousness for a given attribute within a given class, as well as avoiding unnecessary sensitivity at class boundaries. For example, in the case of Dow classification, if after the calculations in determining a compound's flammability is found to be 1.45, then it is presumed to belong to the 'index class 1'. On the other hand, if the calculated value increases by 0.10 to a value of 1.55, then the flammability is ranked in 'index class 2'. This subjective Boolean classification is eliminated by using membership functions that allow an index to belong to more that one class at the same time.

Table 1
Dow and fuzzy logic classification of reactivity and flammability attribute

Hazardous attribute	Dows classification		Fuzzy classification
	Ranking index	Qualitative value	FTDF
Reactivity	0	Stable	(0.0, 0.0, 1.0)
	1	Mild	(0.2, 1.0, 1.8)
	2	Significant	(1.2, 2.0, 2.8)
	3	Vigorous	(2.2, 3.0, 3.8)
	4	Explosive	(3.0, 4.0, 4.0)
Flammability	0	None	(0.0, 0.0, 1.0)
	1	Mild	(0.3, 1.0, 1.7)
	2	Significant	(1.0, 2.0, 3.0)
	3	High	(2.0, 3.0, 4.0)
	4	Very high	(3.0, 4.0, 4.0)

By way of example, we compare reactivities based on Dow's indices and the corresponding fuzzy logic methodology in Table 1. Dow's hazard ranking for reactivity of a hazardous material suggests five levels, where each was assigned a crisp numerical value and a corresponding qualitative linguistic value. It is significant to note that the Dow's qualitative reactivity scaling system contains underlying vagueness and uncertainty, which in this study is described and represented by using fuzzy triangular distribution functions (FTDFs).

Furthermore, in practice, these membership function definitions are dependent upon individual process considerations and therefore can be easily modified or changed on a case-by-case basis. For instance, the membership functions ranges for representing hazard ranking for hazardous waste, where the focus is transportation, may be different from a case focussing on the safety of personnel in a processing plant. In developing the membership functions, it was ensured that the FTDFs were centred on 0, 1, 2, 3, 4 values to reflect the Dow classification in a realistic manner. The membership functions of reactivity attribute are shown in Fig. 1.

Similarly, flammability, corrosivity and toxicity attributes were defined and represented using fuzzy logic sets within their respective universes of discourse. For each linguistic variable, it had an associated specific range of values. To achieve this, fuzzy sets are defined over the universe of discourse for each input valuable [38]. Each of the four primary hazard ranking input variables (flammability, corrosivity, toxicity and reactivity) was defined using five linguistic fuzzy sets represented in the rule base by fuzzy triangular distribution functions.

7. Application of the proposed methodology

Extensive simulation studies were carried out in this work to demonstrate the effectiveness and the validity of the pro-

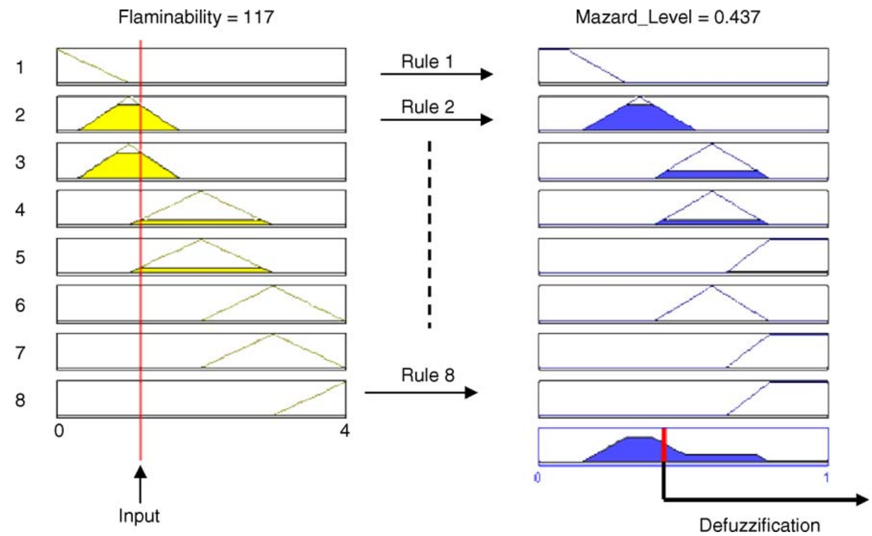

Fig. 4. Graphical representation of the flammability rule base.

posed fuzzy logic methodology in an attempt to derive a single aggregated hazard ranking expressing the degree of hazardousness of a composite waste. In real dynamic and uncertain decision making environment as mentioned before, a tool that can facilitate decision making for decision and policy-makers dealing with hazardous wastes can be considerably useful in reducing the time and resources required in ascertaining a certain waste's hazard overall ranking. As a way of achieving this objective, the knowledge and data obtained from the literature characterized by uncertainty and subjectivity were expressed using fuzzy IF-THEN rules. Therefore, in facilitating transparent and efficient knowledge representation, a hierarchical structure of an aggregative hazardous waste index model was developed, thus enhancing simulation of hazard ranking (see Fig. 3).

7.1. Linguistic rules

The simulation of the FHWI was done by using different sets of IF-THEN rules. In each module, the membership functions, the rules and the rule weights were used to model a continuum of feasible states of hazard level attributes within a defined universe of discourse. It should be noted that not all possible rules were generated in the first level (see Fig. 3). That is, if there are m linguistic variables, each having n membership functions, then all possible output states should be defined by m^n rules. This would have yielded rule bases of flammability, corrosivity, reactivity and toxicity each having five rules. Instead, the rules were derived such that they reflected a realistic mapping of the crisp inputs into linguistic outputs.

For example, in expressing flammability attribute in the fuzzy logic system, eight linguistic IF-THEN rules were generated instead of five. The reasoning process is represented graphically in Fig. 4, while the linguistic expression of the rules and the corresponding rule weights are presented in Table 2. Similarly, IF-THEN rules were derived for modelling the hazard levels associated with corrosivity, toxicity and reactivity, which yielded 8, 10 and 8 rules, respectively.

However, in the evaluation of what is regarded in the literature as the material factor, MF, and referred to in this paper as the aggregated fuzzy flammability–reactivity hazard ranking, the general rule for deriving the IF-THEN rules was applied. This yielded a knowledge rule base of 25 (5^2) rules for computing the aggregated fuzzy flammability–reactivity hazard ranking, because there are two input variables, each having five linguistic values. On the other hand, the rule base for evaluating the overall hazard ranking FHWI required 150 ($5^2 \times 6$) rules because there were three input variables, two of which had five linguistic values, while the third one was described by six linguistic values. Thus, in this instance a total of 209 rules were developed to facilitate the computation of aggregated fuzzy hazardous waste index.

7.2. System testing and validation

The testing procedure begins by checking the response of each knowledge base separately; using data sets of known outcomes. This helped us in regard to fine-tuning the membership functions of each knowledge base and validating the logical reasoning of the fuzzy rule-based system discussed in this paper. For instance, when we used the upper extreme limits of each attribute the overall hazard posed by the waste was ranked as extremely

Table 2
The IF-THEN rules for evaluating linguistic flammability hazard ranking of a composite waste

Rule no.	IF Flammability	THEN Hazard Level	Rule weight
1	None	None	1.00
2	Mild	Low	1.00
3	Mild	Moderate	0.30
4	Significant	Moderate	1.00
5	Significant	High	0.25
6	High	Moderate	0.50
7	High	High	0.80
8	Very high	High	1.00

Table 3
The highest and lowest certainty limits of the fuzzy rankings feasible from the developed fuzzy model

Hazard attribute	Inputs		Output (fuzzy rankings)	
	Lowest value	Highest value	Lowest limit	Highest limit
Flammability	0	4	0.106	0.862
Reactivity	0	4	0.114	0.886
Toxicity (pmm)	Non-toxic (infinity)	0.2	0.0902	0.900
Corrosivity (pH)	7	0 or 14	0.0902	0.900
Flammability–reactivity fuzzy ranking	(0.106, 0.114)	(0.862, 0.886)	0.0672	0.886
Overall hazard ranking	(0.0902, 0.0902, 0.0672)	(0.900, 0.900, 0.886)	0.0373	0.914

severe, with a ranking of 91.4%. In other words, the result of ranking overall hazard when all four contributing attributes were at their most dangerous levels was 0.914 on a scale of 0–1. This is the highest likelihood estimate for the overall fuzzy hazardous waste index with a linguistic value *extremely high*. Note that this was a conservative estimate, as the rules based on heuristics do not offer 100% certainty during the process of computing with words.

On the other hand, the overall fuzzy system evaluation of a benign waste yielded a hazard ranking with a likelihood of 3.73%. In other words, the result of ranking overall hazard when all four contributing attributes were at their best benign status was 0.0373 on a scale of 0–1. Again, this value is conservative, as the heuristics do not accord a 0% certainty. Similar computations were carried out in each knowledge base using maximum and minimum input values, thus yielding the lowest and highest fuzzy rankings as presented in Table 3 on a scale of 0–1.

As a second example illustrating the validity of the proposed approach, we consider the output derived from the fuzzy flammability–reactivity ranking module (see Fig. 3). In practice, the reactivity hazard rating N_r and flammability hazard rating N_f are assigned to crisp numbers in the range 0–4 [13], which in turn are used to compute the material factor, MF, as shown in Table 4. Moreover, the results obtained from these experiments could be used to fine-tune the membership functions of each module and to validate the logical reasoning of the fuzzy rule-based system.

Since the outputs derived from the fuzzy ruled based flammability and reactivity modules are in the range of 0–1, the crisp input values were fixed at 0, 0.25, 0.50, 0.75 and 1.00 for each of the linguistic input variables (just as was the case with the 0, 1, 2, 3 and 4 values in the Dows index). The results of the fuzzy flammability–reactivity hazard rankings are presented in Table 5. In this table it can be seen that the results closely mirror those in Table 4. Clearly this is an indication of the consistency of the process of generating fuzzy IF-THEN rules in the various modules.

The proposed fuzzy system was validated by comparing its results with the output hazard ratings for each of the four hazard attributes on previously studied wastes reported by Gupta and Babu [9]. The hypothetical index inputs reported by Gupta and Babu [9] are summarised in the first two rows of Table 6 and their respective results are presented in Table 7 (first two rows) in the second to fourth columns.

7.3. Application to unknown composite wastes

To demonstrate the applicability of the methodology, rigorous simulations were carried out for different composite wastes. To initiate evaluation of the overall hazard ranking, the user is required to supply quantitative data in terms of component percentages and the hazard rankings for the four hazard attributes as indicated in Fig. 3. Once the system has been fed with all the necessary inputs, the FHWI is computed. As a way of demonstrating the applicability of the model, 12 worked examples are presented in Table 6 and their corresponding fuzzy-based hazard rankings are shown in Table 7. It should be noted that the rankings of the hazard attributes provided by the user are the most important factor in the final fuzzy hazardous waste index ranking suggested by this model. An explanation of the functioning of the fuzzy rule-based system reported here is schematically depicted in Fig. 5.

The fuzzy logic approach (see Fig. 5) described in this paper was applied to examples 1 and 2 for composite hazardous wastes obtained from literature [9], having four and three constituent components, respectively. The results are shown in Table 7. In each simulation run, the system begun by evaluating the aggregated crisp values for the flammability, reactivity, toxicity and corrosivity using Eqs. (1)–(4), respectively.

Table 4
Evaluation of material factor in the Dows system (adopted from reference [13])

N_f	N_r				
	0	1	2	3	4
0	1	14	24	29	40
1	4	14	24	29	40
2	10	14	24	29	40
3	16	16	24	29	40
4	21	21	24	29	40

Table 5
Simulated flammability–reactivity hazard ranking using fuzzy logic approach

HF_F	HR_F				
	0.00	0.25	0.50	0.75	1.00
0.00	0.067	0.350	0.550	0.700	0.876
0.25	0.200	0.350	0.550	0.700	0.876
0.50	0.200	0.350	0.550	0.700	0.876
0.75	0.350	0.350	0.550	0.700	0.876
1.00	0.550	0.550	0.550	0.700	0.876

HF_F, fuzzy flammability hazard index; HR_F, fuzzy reactivity hazard index.

Table 6
A complete data set for hazard rankings of individual constituent components in a composite waste

	C1	C2	C3	C4	C5	NF1	NF2	NF3	NF4	NF5	NR1	NR2	NR3	NR4	NR5	T1	T2	T3	T4	T5	PH
1	0.40	0.20	0.15	0.25	–	3	2	0	0	–	3	1	4	0	–	10	25	200	Inf.	–	11.8
2	0.10	0.20	0.70	–	–	2	4	0	0	–	–	1	0	–	–	2	25	Inf.	–	–	3.6
3	0.15	0.30	0.10	0.25	0.20	0	1	2	0	1	1	1	0	0	1	1000	5000	Inf.	1000	Inf.	7.8
4	0.15	0.30	0.10	0.25	0.20	4	3	2	3	3	1	2	0	0	1	50	25	50	100	100	6.0
5	0.50	0.05	0.15	0.30	–	0	4	3	1	–	1	4	2	3	–	1000	0.2	400	200	Inf.	4.2
6	0.23	0.18	0.30	0.16	0.13	0	1	1	0	3	4	3	3	2	4	1500	1000	5000	400	1000	8.0
7	0.36	0.41	0.23	–	–	1	2	0	–	–	1	1	0	–	–	5000	1000	5000	–	–	1.5
8	0.10	0.25	0.20	0.30	0.15	2	3	4	2	3	3	3	2	3	1	50	10	5	100	200	13.4
9	0.10	0.25	0.20	0.30	0.15	2	0	1	0	0	1	1	0	1	0	Inf.	Inf.	Inf.	2000	5000	5.5
10	0.23	0.31	0.18	0.27	–	0	0	1	0	–	2	0	1	0	–	Inf.	Inf.	1000	Inf.	–	8.3
11	0.23	0.31	0.18	0.27	–	0	0	1	0	–	0	1	0	0	0	Inf.	Inf.	1000	Inf.	Inf.	8.3
12	0.35	0.45	0.20	–	–	0	0	1	–	–	0	0	1	0	0	Inf.	Inf.	2000	–	–	8.5

C's, NF's, NR's and T's represent constituent components, NFPA rankings for flammability, reactivity and toxicity, respectively. Inf. denotes non toxic.

In the case of examples 1 and 2, the results obtained for flammability, corrosivity and toxicity hazard indices are the same as those reported by Gupta and Babu [9] (see respective values in columns 2–4 in Table 7). In order to compute an aggregated overall hazarding ranking of a composite waste, the derived values for each attribute were used as fuzzy numbers to generate the corresponding fuzzy hazard rankings. In example 1, the system computed a linguistic output value for each attribute whose corresponding defuzzified crisp value is shown in columns 6–8 in Table 7 (flammability, reactivity, and toxicity, respectively). It should be noted that the computed hazard rankings were not rounded as was the case in the work of Gupta and Babu [9] in order to facilitate the final ranking of the waste. Rather, the fuzzy logic approach offered an alternative, owing to its ability to deal explicitly with values within intermediate classes.

In addition, after the system obtained the hazard ranking associated with each attribute denoted as H1, H2, H3 and H4 in Table 7, the next step involved approximating a linguistic label of each output in these columns. In the case of example 1, the flammability is characterized by the linguistic label *moderate*, reactivity as *moderate* to *high*, toxicity as *toxic*, while corrosivity is assigned a *moderate* to *high* hazard ranking. These linguistic values were then used in the next rule base in the hierarchical structure to compute a fuzzy flammability–reactivity hazard ranking, as well as the overall hazard ranking of the composite waste.

Using the defuzzified crisp inputs 0.59 and 0.69 computed from the flammability and reactivity rule modules yielded a fuzzy flammability–reactivity hazard ranking labelled as *high* (0.68). Since at this stage the system has completed the evaluation of the required parameters, the final computation stage of the FHWI commences. Using the linguistic labels of the fuzzy flammability, reactivity, toxicity and corrosivity hazard rankings previously computed, the FHWI for the composite waste in example 1 rated as *extremely high*. Its corresponding single-value output on a scale of zero to one is 0.89. Similar computations were carried out in example 2, where the FHWI was rated as *very high* and the single-value output as 0.75.

Note that the overall waste hazard ranking in example 1 is higher than in example 2. This is because the approach proposed in this study takes into account the contribution of each of the four attributes. Therefore, while in example 2 both the toxicity and corrosivity hazard rankings were high, the flammability and

Table 7
Complete set of system results based on inputs shown in Table 6

	HF	HR	HT	HC_F (H1)	HF_F (H2)	HR_F (H3)	HT_F (H4)	HFR_F (H5)	OHR	Final hazard ranking
1	1.600	2.000	4.880	0.6744	0.5943	0.6913	0.7043	0.6804	0.8914	EVHHR (1)
2	1.000	0.200	5.800	0.5216	0.4305	0.1199	0.8930	0.2000	0.7500	VHHR (1)
3	0.700	0.650	0.046	0.0902	0.3449	0.3121	0.0908	0.3700	0.3000	LHR (1)
4	3.050	0.950	2.250	0.0902	0.7583	0.4078	0.0902	0.3607	0.5074	MHR (0.426)
5	0.950	1.900	25.238	0.4268	0.4168	0.6868	0.9005	0.6731	0.8784	EVHHR (1)
6	1.170	3.200	0.0923	0.2393	0.4369	0.7516	0.0914	0.7075	0.6129	HHR (0.874)
7	1.180	0.770	0.0302	0.7911	0.4375	0.3496	0.0906	0.4125	0.6233	HHR (0.767)
8	2.800	2.500	7.0750	0.8242	0.7548	0.7331	0.9005	0.7000	0.9116	EVHHR (1)
9	0.800	0.650	0.180	0.2393	0.3754	0.3121	0.0908	0.3740	0.3000	LHR (1)
10	0.180	0.890	0.018	0.1917	0.1115	0.3877	0.0904	0.4521	0.3776	MHR (0.224) LHR (0.276)
11	0.180	0.180	0.018	0.1917	0.1115	0.1193	0.0904	0.0699	0.1159	VLHR (0.659)
12	0.200	0.400	0.010	0.2393	0.1122	0.2243	0.0903	0.2912	0.2771	LHR (0.776)

VL, very low, L, low, M, moderate, H, high, VH, very high, EVHHR, extremely very high; HF, aggregated flammability hazard index; HR, aggregated reactivity hazard index; HT, aggregated toxicity hazard index; HC_F, fuzzy corrosivity hazard index; HF_F, fuzzy flammability hazard index; HR_F, fuzzy reactivity hazard index; HT_F, fuzzy toxicity hazard index; HFR_F, fuzzy flammability–reactivity hazard index; OHR, overall hazard ranking.

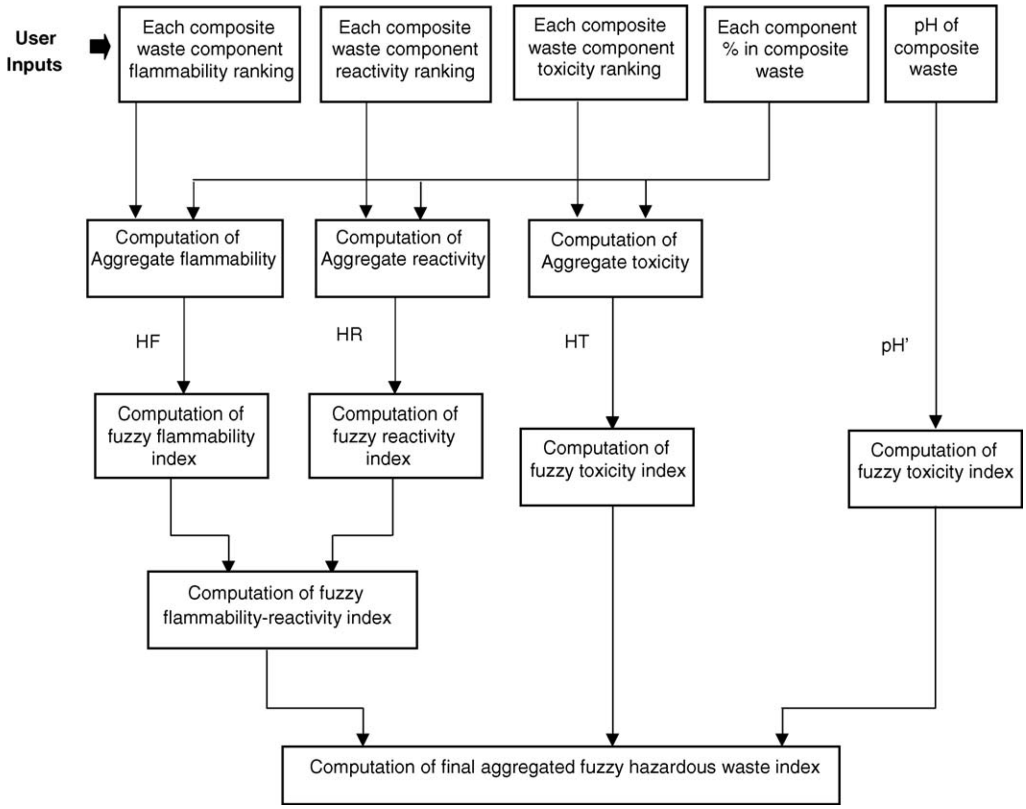

Fig. 5. Explanation of the functioning of fuzzy rule-based system.

reactivity were very low, thus forcing the system to rank the aggregated FHWI one level of magnitude lower than in example 1, where all the attributes were rated as relatively moderate to high. By following the same procedure in each experimental run, the results in Table 7 show that an aggregated fuzzy hazardous waste index can be computed for any composite waste, regardless of the number of its constituent components.

8. Conclusion

The use of an aggregated single-value index to express the overall hazard ranking of a waste will be appealing to a wide range of experts and industrialists dealing with composite hazardous wastes. Thus, in this work we have proposed a fuzzy rule-based system for computing a single-value FHWI motivated by the classical methodology introduced by Gupta and Babu [9] for computing hazardous waste index (HWI).

The purpose of this index is to provide the users with a versatile and robust tool suitable for rapidly assessing the status of the waste's overall hazard ranking by using the known attributes of the constituent components. The results show that the application of fuzzy logic in analyzing and quantifying the ranking of hazardous wastes eliminates the problem of forcing the ranking to a particular class, owing to the rigidity of Boolean mathematical approaches. Thus the tool meets most of the desired features outlined by Khan et al. [27] to quantify the level of hazardousness of a given composite waste.

The FHWI represents a novel approach to determine the hazard ranking of a composite waste without using weighted averaging techniques to combine the final individual rankings of flammability, reactivity, toxicity and corrosivity as suggested by Rajeshwar et al. [11]. However, the fuzzy approach discussed in this paper offers an alternative with the ability to exploit the experience of human experts borne out of many years of experience and in addition to the IF-THEN rules derived from data.

The decision tool is faced with two challenges. Currently, in most practices we acknowledge that individual quantities of constituent components of composite wastes are poorly documented in operations such as handling, generating, transporting and recycling. However, as legislation is becoming more stringent globally, the potential benefits of the decision support system could be fully exploited. Moreover, the system does not take into account the possibility of new compounds that may be formed, owing to the reactions of the constituent elements. This may result in an overall hazardousness varying considerably, even from benign to a highly hazardous status.

Notably, as more data in the field of hazardous waste become available from industry and academia, the tool described in this paper can be refined further to increase its reliability, validity and dependability.

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