A Quantitative Feasibility Model for Singapore Waste-to-Energy Ash as a Zeolitic Material Feedstock

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Abstract

In Singapore's waste management system, waste-to-energy ash is a major by-product but is viewed as a residue to be managed rather than a material resource. This paper examines whether Singapore waste-to-energy ash could be used as a feedstock for zeolitic material synthesis, when assessed through a quantitative feasibility model rather than a descriptive review. In this study a mathematical framework is developed based on five criteria - technical suitability, environmental safety, scalability, cost plausibility, and circular resource value. The model also includes two threshold conditions and a nonlinear penalty for impurity or risk burden. This ensures that feasibility is treated as a constrained and a multi-factor problem rather than a general sustainability claim. The aim of this paper is not to prove from scratch that ash-to-zeolitic conversion is scientifically possible, as supported in the wider literature, instead this paper assesses if this pathway is realistic in the Singapore context. The baseline model produces a feasibility score of F = 0.351, indicating qualified but constrained feasibility. Sensitivity analysis produces scores between F = 0.323 and F = 0.382 under plausible variations in model assumptions, while stricter technical or environmental threshold conditions reduce the feasibility score to F = 0. By shifting focus on Singapore-specific implementation feasibility from general scientific possibility, the paper positions ash-valorisation as a higher-value circular materials question rather than only a waste management issue. The results indicate that such a pathway represents a credible but condition-dependent higher-value ash-valorisation option, rather than an immediate alternative to current reuse approaches.

Keywords: Waste-to-energy ash; zeolitic material; feasibility modelling; circular economy; Singapore; resource recovery; sensitivity analysis; waste-derived materials; sustainability

Introduction

Singapore's solid waste system is built around waste-to-energy incineration. According to the National Environment Agency (NEA), incineration reduces the volume of waste by about 90 percent but it leaves behind residues that must be managed and disposed[1,2]. Along with non-incinerable waste, the ash residues are sent to Semakau Landfill. This means that even a highly efficient waste system remains dependent on limited landfill space. This space is likely to be exhausted by the year 2035 as estimated by NEA Singapore. In addition, Singapore's ash-valorisation efforts have focused on lower-value but practical reuse routes, like NEWSand. Treated incinerated bottom ash and slag have been explored as construction materials for road-base, sub-base layers, and non-structural concrete.

This raises an important next stage question. If ash is already treated as a recoverable material in construction-related applications, it is vital to understand if selected ash streams can also be evaluated for higher-value functional uses or not. One such possibility is zeolitic material synthesis. These materials are widely studied because of their porous structure, ion-exchange capacity, and relevance to adsorption and environmental remediation. This study does not begin with the claim that ash-to-zeolite conversion is a completely new idea, as this broader scientific possibility is already supported in the international literature. The real issue is narrower and more practical, whether the use of Singapore waste-to-energy ash as a feedstock for zeolitic material synthesis appears realistically feasible when examined under local technical, environmental, circular economy, and other constraints.

Singapore's setting makes this question even more relevant. Currently, Singapore's ash strategy is shaped by two pressures which are the need to reduce disposal to Semakau and the need to develop circular uses for residual materials. NEA has explicitly stated that the NEWSand is intended to close the waste loop and extend the lifespan of Semakau Landfill[3]. In addition, Singapore's research system has also shown a broader interest in waste-to-resource pathways. NTU and NEA have jointly developed Waste-to-Energy Research Facility (WTERF) to explore technologies for converting waste into energy and useful materials[4,5]. At NUS, work on the circular materials economy, including Professor Seeram Ramakrishna's research profile, emphasizes materials circularity across waste, water, and food systems[6,7]. These developments show that the national direction is no longer limited to waste reduction alone, instead, it actively includes resource recovery and material circularity.

This paper is built on that broader direction but also occupies a specific position. This paper does not claim that Singapore is not already doing anything with ash, nor does it claim that zeolitic conversion has not been demonstrated elsewhere. This paper asks whether a Singapore-focused zeolitic pathway can be evaluated more rigorously through a quantitative feasibility model. This distinction is important because a pathway may be scientifically plausible in general but still be locally weak when other factors like compositional suitability, environmental safety, scalability, cost plausibility, and circular resource value are considered together. The purpose of the paper is not advocating an immediate implementation but to assess if this pathway is credible enough to merit further attention as a higher-value ash-valorisation option.

With the growing interest in ash-valorisation and the broader scientific plausibility of ash-to-zeolitic conversion, there still is a gap between proof-of-concept material pathways and Singapore-specific implementation assessment. The existing literature does not clearly provide a quantitative framework for evaluating if this pathway is realistically viable under Singapore's technical, environmental, scalability, cost, circular-economy and impurity-related risk conditions. This paper addresses that gap by developing a quantitative feasibility model for the use of Singapore waste-to-energy ash as a feedstock for zeolitic material synthesis. The aim of this study is to treat feasibility as a constrained, multi-factor problem rather than as a general sustainability claim. The paper represents a shift from conceptual possibility to structured evaluation.

Research Gap and Contribution

International research shows that ash-derived zeolitic pathways are plausible, and Singapore's own ash strategy already treats incineration residues as materials that can be recovered or reused and that is achieved through NEWSand and construction materials. NEA explicitly links this effort to closing the waste loop and extending the lifespan of Semakau Landfill. Hence, neither ash-valorisation nor converting ash into useful materials is novel.

The unresolved question is whether a zeolitic pathway is realistically viable in Singapore and not if it is scientifically possible. The contribution of this paper is narrow and important. It does not claim experimental synthesis and it does not present ash-to-zeolitic conversion as a new invention. It develops a quantitative feasibility model to evaluate whether the use of Singapore waste-to-energy ash as a feedstock for zeolitic material synthesis deserves consideration as a high-value circular materials pathway within Singapore's current ash-valorisation landscape. Paper moves the discussion from general possibility to structured local evaluation.

Research Objective

The objective of this study is to develop a quantitative feasibility model for evaluating whether the use of Singapore waste-to-energy ash as a feedstock for zeolite material synthesis is practically viable under criteria such as technical, environmental, scalability, cost, and circular-economy while accounting for impurity-related risk.

Accordingly, this study is guided by the following research question:

To what extent is the use of Singapore waste-to-energy ash as a feedstock for zeolitic material synthesis feasible when evaluated through a quantitative model based on technical suitability, environmental safety, scalability, cost plausibility, circular-resource value, and impurity-related risk?

Methodology

This study adopts a conceptual quantitative feasibility approach. It does not test ash-to-zeolitic conversion experimentally, instead, it evaluates its practical viability in the Singapore context through a structured mathematical model. Feasibility here is treated as a constrained multi-variable problem shaped by five criteria that capture the main conditions under which the pathway would succeed or fail and realistically justified beyond proof-of-concept interest.

The model is built around five positive feasibility dimensions which are technical suitability, environmental safety, scalability (implementation potential), cost plausibility, and circular-resource value.

In addition, a separate risk or impurity burden term is included in the study to account for negative factors that may reduce feasibility even when the core criteria appear favourable. Which means, that the five core criteria are treated as positive variables, where a higher normalized value increases feasibility, whereas the penalty variable is treated inversely and reduces the final feasibility outcome.

To make the criteria mathematically comparable, each variable is normalized to a common scale from 0 to 1. The normalized values are then combined in a constrained weighted feasibility model that includes a nonlinear penalty term, with the total weight is constrained to equal 1. This allows the model to represent feasibility as a structured multivariable relationship rather than as an informal qualitative assessment. Hence, for modelling purposes, impurity burden and the related constraints, like contamination risk, are represented through a single penalty variable that captures the overall negative effect of residual risk on feasibility.

The methodology also incorporates threshold conditions for criteria that cannot reasonably be compromised. It prevents strong performance in one area from masking failure in another. This keeps the model grounded in implementation reality. This is important because certain weaknesses are non-compensable, for example, strong performance in circular -resource value cannot offset unacceptable technical or environmental weakness.

A nonlinear penalty term is introduced to reflect the possibility that impurity burden or contamination risk may reduce overall feasibility disproportionately rather than in a simple linear way and this may happen especially when those risks move beyond an acceptable range.

Finally, sensitivity analysis is conducted by varying criterion weights, threshold values, and penalty intensity. In this step the model is examined on how strongly the feasibility outcome depends on changes in weights and assumptions. It studies if the overall conclusion remains stable under different plausible conditions or not. Hence, the methodology aims to calculate the feasibility result and also evaluate the robustness of the result.

The model inputs are derived from published literature on ash-derived zeolitic pathways, reported characteristics of waste-to-energy ash, and Singapore's ash management context. Hence, they are literature-derived and context-informed rather than experimentally measured within this study. Wherever direct quantitative values are not uniformly available, variables are assigned through bounded and transparent normalization rules based on reported ranges, comparative evidence, and implementation-relevant constraints.

Technical suitability captures whether the ash can reasonably function as a precursor-material, environmental safety addresses contamination and residual risk, scalability reflects whether the pathway could move beyond laboratory interest, cost plausibility considers economic realism, and circular resource value captures if the pathway adds meaningful recovery value within a resource constraint urban system.

The model is intended as an implementation-oriented screening framework and not a substitute for experimental synthesis, pilot-scale validation, or full techno-economic analysis.

Most importantly, the model is framed specifically around Singapore's current ash-management context, which means feasibility is not evaluated in abstract terms but in relation to local disposal pressure, existing ash-reuse pathways, and circular resource priorities.

Model Structure

Main Feasibility equation

To evaluate the pathway in a structured way, the study represents overall feasibility as a constrained weighted function. The model is designed so that positive implementation factors raise feasibility while impurity-related risk reduces it. It is expressed as:

$$F = \begin{cases} (w_T t + w_E e + w_S s + w_C c + w_R r + \alpha t s)\, e^{-\lambda p}, & t \geq t_0, e \geq e_0 \\ 0, & otherwise \end{cases}$$

Where, $F \rightarrow$ overall feasibility score.

Variables *t, e, s, c, r* $\rightarrow$ represent the normalized values of technical suitability, environmental safety, scalability, cost plausibility, and circular-resource value respectively.

Variable $p \rightarrow$ penalty term for impurity burden and related residual risk.

Coefficients $w_T, w_E, w_S, w_C, w_R \rightarrow$ weights assigned to the five positive criteria, subject to the condition;

$$w_T + w_E + w_S + w_C + w_R = 1, w_i \geq 0$$

αts → captures the interaction between technical suitability and scalability, which reflects that technical promise is more meaningful when the pathway is capable of practical expansion.

$e^{-\lambda p} \rightarrow$ applies a non-linear penalty to the model, and allows impurity burden and risk constraints to suppress feasibility more sharply as risk increases. The parameter λ controls the strength of this penalty.

t_0, e_0 → threshold values, representing minimum acceptable values of technical suitability and environmental safety. If any of these falls below the threshold, the pathway is treated as infeasible with the feasibility score is set to zero. The idea is to prevent strong performance of one criterion from masking failure in conditions that are fundamental to realistic implementation.

The model treats feasibility as a constrained multivariable relationship rather than a descriptive impression. The model allows the pathway to be assessed in a mathematically explicit way, transparent in its assumptions, and suitable for sensitivity testing.

Definition of variables

Table1. The variables and parameters used in the feasibility model.

The five core criteria (*t, e, s, c, r*) are treated as positive contributors to feasibility, while *p* functions as a penalty term, t_0, e_0 and the threshold parameters define minimal admissibility conditions.

Symbol	Term	Definition	Model Role
T	Technical suitability	Extent to which Singapore's waste-to-energy ash appears suitable as a precursor for zeolitic material synthesis under known process conditions.	Positive criterion

E	Environmental safety	Extent to which the pathway appears environmentally acceptable in relation to contamination risk and residual hazard.	Positive criterion
S	Scalability	Extent to which the pathway appears capable of moving beyond proof-of-concept towards broader practical application	Positive criterion
c	Cost plausibility	Extent to which the pathway appears economically reasonable in terms of precursor handling, processing demands, and implementation practicality.	Positive criterion
R	Circular-resource value	Extent to which the pathway contributes to higher-value material recovery within a circular economy framework.	Positive criterion
P	Penalty variable	Combined measure of impurity burden and related residual risk.	Negative term
w_T	Weight for technical suitability	Relative importance assigned to technical suitability.	Weight
w_E	Weight for environmental safety	Relative importance assigned to environmental safety.	Weight
w_S	Weight for scalability	Relative importance assigned to scalability.	Weight
w_C	Weight for cost plausibility	Relative importance assigned to cost plausibility.	Weight
w_R	Weight for circular-resource value	Relative importance assigned to circular-resource value.	Weight
α	Interaction coefficient	Coefficient representing the interaction between technical suitability and scalability.	Interaction parameter
λ	Penalty coefficient	Coefficient controlling the strength of the non-linear penalty term.	Penalty parameter

t_0	Technical threshold	Minimum acceptable value for technical suitability.	Threshold
e_0	Environmental threshold	Minimum acceptable value for environmental safety.	Threshold

Normalization and Weighting Framework

The selected criteria represent different kinds of conditions and may be expressed on different scales. Each positive criterion is normalized to a common interval from 0 to1 to make the criteria mathematically comparable. In the interval, 0 represents the least favourable condition while 1 is the most favourable condition within the bounds of the model. This ensures that no criterion exerts disproportionate influence because of its original scale.

$$x_i = (X_i - X_i^{min})/(X_i^{max} - X_i^{min})$$

Where X_i is the original value of the criterion, and X_i^{max}, X_i^{min} are the lower and upper bounds used for normalization.

The same principle is applied to the penalty variable. Its effect is treated inversely in the model as a higher penalty reduces the overall feasibility of the model.

The normalized criteria are then combined using the weighted structure. The weights w_T, w_E, w_S, w_C, w_R represent the relative importance assigned to the five positive criteria (as listed above), subject to the condition;

$$w_T + w_E + w_S + w_C + w_R = 1, w_i \geq 0$$

This constraint keeps the model internally consistent and ensures that the final feasibility score reflects a defined distribution of importance across the selected criteria. The weighted scheme is used here as a structured representation of relative priority, not as a claim that any single weighting pattern is universally fixed. Later, the model is tested through sensitivity analysis to examine whether the feasibility outcome remains stable under plausible alternative assumptions.

Threshold conditions and Penalty Structure

The model includes threshold conditions for technical suitability and environmental safety which are denoted by t_0, e_0 respectively. These thresholds are necessary in the model because certain weaknesses cannot reasonably be compensated for, by strengths elsewhere in the model. A pathway may appear favourable in terms of circular-resource value or scalability, but still it cannot be regarded as feasible if it fails to meet technical suitability or environmental safety requirements. Accordingly, the feasibility score is set to zero whenever either threshold is not satisfied.

The model also includes non-linear penalty term for impurity burden and residual risk. This penalty is treated nonlinearly because constraints related to contamination are unlikely to affect feasibility in a strictly proportional manner. A larger increase in impurity burden may reduce viability sharply once acceptable limits are approached or exceeded, whereas modest increase in impurity burden may remain manageable. Hence, the penalty term is intended to capture escalating implementation risk rather than a simple linear deduction.

In practical terms, the model assumes that stronger performance in one criterion cannot fully offset failure in another. This makes the model more realistic than a simple additive scoring framework, which may overstate feasibility by treating all trade-offs as fully compensable.

Sensitivity analysis design

As feasibility model is dependent on the weighted criteria and threshold assumptions, its conclusion cannot be treated as reliable unless it remains reasonably stable under variation. That’s the reason the model is tested through sensitivity analysis. The aim is to determine how strongly the final feasibility outcome is dependent on the weighted structure, threshold values, and the penalty intensity.

Sensitivity analysis is conducted by varying the weights assigned to the five positive criteria while the conditions that their sum remains 1 is kept constant. The threshold values for technical suitability and environmental safety, and the penalty coefficient, λ are also adjusted within plausible ranges. With this setup, it can be assessed whether the model produces a robust result or it changes substantially under alternative (but still reasonable) assumptions.

To support this analysis, the model is further examined under three broad scenarios: optimistic, moderate, and constrained. These scenarios do not predict exact outcome, but they represent different combinations of favourable, balanced, and limiting conditions. In this way, the sensitivity analysis helps distinguish between a pathway which is consistently feasible and a pathway where feasibility depends on a narrow set of assumptions.

This step makes the model interpretation more cautious and rigorous. Rather than relying on a single calculated score, the study evaluates whether the feasibility outcome remains credible across multiple plausible configurations of the model.

Model input and scoring basis

The inputs used in the feasibility model are derived from these sources: published literature on ash-derived zeolitic pathways, Singapore-specific implementation context, and bounded model assumptions where directly comparable values are not consistently available. The model is evidence-informed and not based on experimental measurements.

For each criterion, assigned values are anchored either to reported findings in the literature or to the implementation-related constraint in the Singapore context. Wherever the available evidence does not support a single direct quantitative value, bounded scoring is used within transparent limits, and the effect of those assumptions is later tested through sensitivity analysis. With that the scoring framework remains structured and explicit without claiming a level precision that the underlying evidence cannot support.

Weighting Basis

The weighting structure is used to represent the relative importance of the five positive feasibility criteria within the model. In the absence of a single empirically established weighting scheme for this pathway, the study begins from the transparent baseline and then tests the effect of variation through sensitivity analysis. This approach is intended to avoid presenting any one weighted pattern as fixed or universally valid.

In practical terms, the weights are treated as model assumptions that express relative priority rather than exact measured quantities. Their role is not to determine the outcome but to make explicit how different judgements of importance may affect the final feasibility result. For that reason, the interpretation of the model does not rest on a single weighted choice, but on whether the result remains credible across multiple plausible weighting configurations.

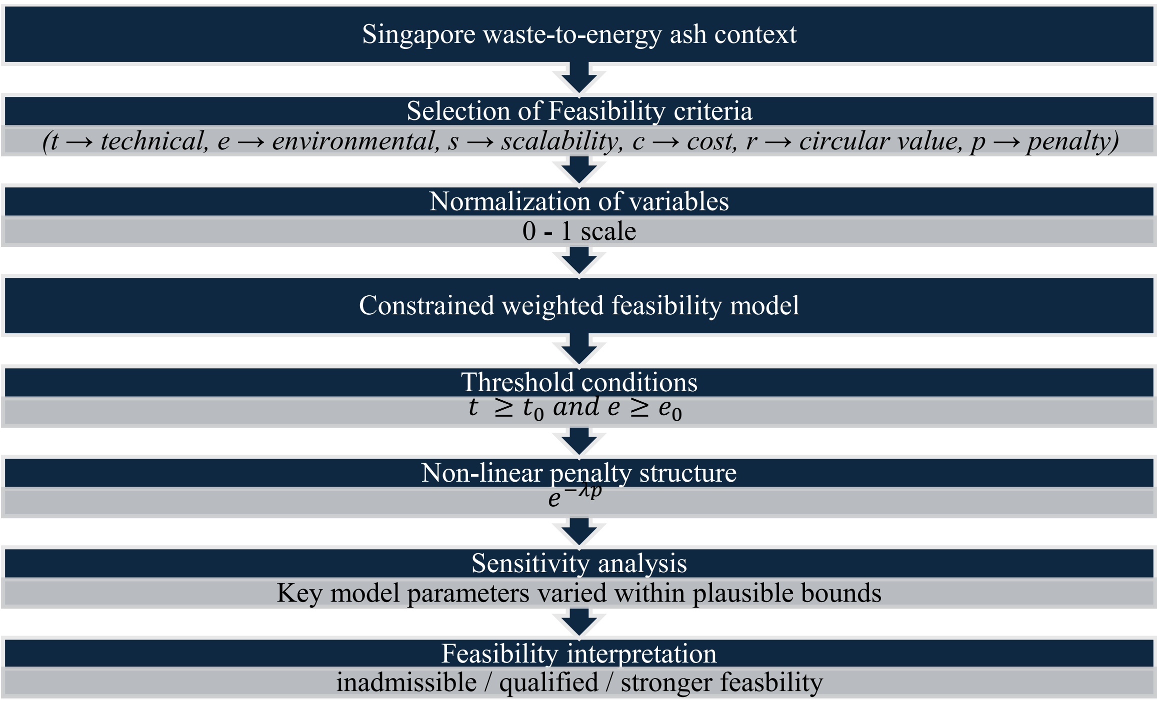
Table 2. Scenario structure used in the feasibility model.

Scenario	General Interpretation	Expected model condition
Optimistic	Favourable technical and implementation conditions with lower residual risk.	Higher positive criteria, lower penalty pressure**.**

Moderate	Balanced conditions without strongly favourable or strongly adverse assumptions.	Intermediate positive criteria, moderate penalty pressure.
Constrained	Less favourable technical and implementation conditions with stronger residual risk.	Lower positive criteria, higher penalty pressure.

Model Flow Diagram

Figure 1. Conceptual flow of the quantitative feasibility model used in this study.



Application of the Model to the Singapore Context

The model is applied in the Singapore context as a screening framework. It does not produce plant-level engineering prediction but assesses the credibility of the use of waste-to-energy ash for zeolitic material synthesis. This provides a basis to further justify investigation within Singapore's current ash-valorisation landscape.

Singapore already recognizes ash as a recoverable material stream and its current visible reuse pathway remains focused on construction-related applications; hence, this model is relevant. This study uses the model to examine whether a higher-value route can be evaluated in a structured way. The model distinguishes between three broad outcomes: Inadmissibility, qualified feasibility, and stronger feasibility under the selected criteria. A low result will suggest that the pathway is constrained by technical, environmental, or other implementation-related barriers. A moderate result would indicate that the pathway may need further investigation and cannot be regarded as robust. A stronger result would suggest that the pathway deserves more serious consideration as a higher-value ash-valorisation option, subject to experimental and techno-economic validation.

When used in this way, the model provides basis for evaluation. Its value lies in discussing and clarifying how the pathway should be judged under explicit assumptions and also identifying which factors shape the judgement more strongly.

Literature Grounded Model Inputs and Scenario Evaluation

Purpose and Input Basis

This section applies the feasibility model using literature grounded and context-informed inputs. The purpose is to populate the model in a transparent and defensible way using published evidence, Singapore-specific implementation context, and bounded assumptions where directly comparable values are not consistently available. Hence, the model is used as an evidence-informed screening framework rather than a substitute for experimental validation.

Evidence Basis for Model Inputs

The model inputs are grounded in three source types: official Singapore waste-management documents, Singapore-linked research on ash characteristics and valorisation, and the broader international literature on ash-to-zeolitic conversion.

Table 3. Evidence basis for model inputs.

Defines specific source basis for each criterion.

Symbol	Criterion	Specific source basis	What it informs	Assignment type
t	Technical suitability	International studies and reviews on zeolitic synthesis from municipal solid waste incineration ash[8,9]	Scientific plausibility of using incineration ash as a precursor for zeolitic material synthesis.	Literature-grounded screening value.
e	Environmental safety	Singapore-linked ash characterization and contamination studies[10,11]	Heavy-metal burden, ash composition, and contamination-related constraints relevant to environmental admissibility.	Literature-grounded screening value.
s	Scalability	NEA sources on Singapore's waste-to-energy and ash management infrastructure[1,2]	Extent of the gap between laboratory plausibility and practical implementation within Singapore's current system.	Context-informed screening assignment.
c	Cost plausibility	Process demands implied by the broader synthesis literature along with Singapore's implementation context[1,8,9]	Screening-level judgement of economic reasonableness.	Context-informed screening assignment.
r	Circular-resource value	NEA's current ash-reuse strategy, especially, NEWSand and Semakau-likespan-extension framing[1,3,12]	If zeolitic recovery would represent a higher value route rather than currently visible reuse pathways.	Singapore-context informed screening assignment.
p	Penalty variable	Singapore-linked ash characterization and	Combined negative impact of impurity burden and	Literature-grounded

		contamination-related evidence[10,11]	contamination related constraints.	bounded assignments

These sources allow the model to be populated in a way that is evidence-informed as well as appropriately cautious. Directly reported literature is used where available, while bounded assignments are used where the evidence supports structured judgement rather than a single measured value.

Baseline Inputs Assignment

Baseline inputs are assigned as evidence-informed screening values based on the source structure outlined in the above section (Table 3).

Directly comparable Singapore-specific quantitative values are not available for every criterion hence the baseline combines literature-grounded screening values with context informed screening assignments. These values are not presented as direct experimental measurements but are applied as a transparent and defensible reference case for the initial model application.

The purpose is consistent with the screening role of the model and with the current Singapore context, in which official ash reuse is publicly visible mainly through pathways such as NEWSand, instead of a public operational zeolitic-material route.

To make the selected criteria mathematically comparable, each positive value is normalized to a common interval from 0 to 1 before being incorporated into the feasibility model.

Table 4. Baseline input assignment for the feasibility model.

Symbol	Criterion	Baseline value	Basis for assignment
T	Technical suitability	0.62	Set above neutrality because ash-to-zeolitic conversion is supported in the broader literature. But kept below strong feasibility because Singapore-specific implementation remains unestablished[8,9]
E	Environmental safety	0.56	Set only slightly above neutrality because Singapore-linked ash studies indicate

			composition and contamination-related concerns which cannot be ignored even if they do not make the pathway automatically inadmissible[3,10,11]
S	Scalability	0.40	Set below neutrality because the pathway remains at a research or screening stage and is not a part of Singapore's visible mainstream ash-reuse implementation. It remains focused on construction-related reuse rather than zeolitic material deployment[1,2,3]
C	Cost plausibility	0.38	Set below neutrality because the route is likely to involve additional processing and handling demands beyond current lower-level reuse pathways, also no Singapore-specific techno-economic basis is yet established[1,8,9]
R	Circular-resource value	0.74	Set clearly above neutrality because a zeolitic material pathway would represent a potentially higher-value recovery route than currently visible construction-focused reuse pathways such as NEWSand[1,3,12]
P	Penalty variable	0.42	Set at a moderate level to reflect residual impurity burden and contamination-related risk indicated by Singapore-linked ash-characterization evidence, without assuming extreme inadmissibility[10,11]

The baseline values should be read as evidence-informed screening assignments rather than experimentally measured parameters. The baseline pattern reflects a pathway that is scientifically plausible and potentially attractive from circular-resource perspective, but constrained by safety, scale, and implementation uncertainty in the present Singapore context.

Weighted Basis and Baseline Weight Assignment.

The weighted structure is used to represent the relative importance of the five positive criteria within the feasibility model. These weights are not directly observed empirical quantities.

They are model assumptions that reflect the logic of screening and are justified by the structure of the problem.

In this study technical suitability and environmental safety are given the greatest weight as they function as the most fundamental admissibility conditions. A pathway that lacks sufficient precursor suitability or is below acceptable environmental standards, is not considered a credible pathway, even if the other criteria are strong. Circular-resource value is also kept a high weight because the paper is specifically concerned with the justification of the higher-value route within Singapore's current ash-valorisation landscape. Scalability remains important but is weighted slightly lower because it becomes relevant only after technical and environmental admissibility are satisfied. Cost plausibility is included explicitly but is limited in terms of its importance because the study does not attempt a full techno-economic analysis.

Table 5. The baseline weighted scheme used in the model.

Criterion	Definition	Weight	Basis of weight
w_T	Weight for technical suitability	0.24	Fundamental to whether the pathway is materially or process-wise credible.
w_E	Weight for environmental safety	0.24	Whether the pathway is admissible in practical terms.
w_S	Weight for scalability	0.18	Important for implementation but secondary to technical and environmental admissibility.
w_C	Weight for cost plausibility	0.14	Relevant, treated more cautiously as a full techno-economic model is not attempted.
w_R	Weight for circular-resource value	0.20	Central to judging whether the pathway offers meaningful value beyond lower-value reuse.

subject to the condition;

$$w_T + w_E + w_S + w_C + w_R = 1, w_i \geq 0$$

This condition ensures that the weighting structure remains internally consistent and the total contribution of the positive criteria is bounded within the model. The weighted pattern is intended to be transparent rather than definitive. It provides a justified baseline structure for the initial model calculation. Later, sensitivity analysis tests whether the overall result remains credible under different weighting configurations.

Baseline Model Calculation

For the baseline case, the assigned values are:

$$\alpha = 0.10, \qquad \lambda = 1.20, \qquad t_0 = 0.50, \quad e_0 = 0.50$$

Where α is used to represent a modest positive interaction between technical suitability and scalability. λ is used to impose a moderate nonlinear penalty for impurity-related risk. t_0, e_0 are used as midpoint admissibility thresholds on the normalized 0-1 scale.

Calculating feasibility:

$$F = \ (w_T t + w_E e + w_S s + w_C c + w_R r + \alpha t s)\ e^{-\lambda p}$$

Substituting the values:

F = [(0.24) (0.62) + (0.24) (0.56) + (0.18) (0.40) + (0.14) (0.38) +(0.20) (0.74) + (0.10) (0.62 × 0.40)] $e^{-(1.20)(0.42)}$

F = [0.1488 + 0.1344 + 0.0720 + 0.0532 + 0.1480 + 0.0248] $e^{-0.504}$

$F = (0.5812)\ e^{-0.504}$

$F \approx (0.5812)\ (0.6044) \approx 0.351$

The result suggests that under the baseline assumptions used in the study, the pathway is not inadmissible but remains meaningfully constrained. The model does not support strong feasibility at baseline. It points to a pathway that remains scientifically plausible and circularly attractive, but weakened by implementation distance, moderate environmental constraints, and impurity-related risk.

Sensitivity Testing

The feasibility score depends partly on model assumptions; hence, the baseline results are tested for robustness. In this study, sensitivity testing is used to examine whether the baseline conclusion changes materially when key model parameters are varied within plausible bounds. It does not generate new empirical observations, but it determines whether the baseline result is stable or fragile.

Three forms of testing are applied. Firstly, the penalty coefficient is varied to test how strongly the result depends on the impurity-related risk. Then the environmental and technical thresholds are adjusted to assess whether the pathway remains admissible under stricter minimum conditions. After that the weighting structure is altered to examine whether the baseline conclusion is overly dependent on one specific distribution of importance across the five positive criteria.

Table 6. Sensitivity testing of the baseline result.

Test case	**Adjustment**	**Feasibility score *F***	**Interpretation**
Baseline case	$\lambda = 1.20,\ t_0 = 0.50,\ e_0 = 0.50$	0.351	Qualified but constrained feasibility
Lower penalty intensity	$\lambda = 1.00$	0.382	Feasibility improves modestly
Higher penalty intensity	$\lambda = 1.40$	0.323	Feasibility weakens further
Stricter environmental threshold	$e_0 = 0.57$	0.000	Pathway becomes inadmissible
Stricter technical threshold	$t_0 = 0.65$	0.000	Pathway becomes inadmissible
Equal weighting test	$w_T = w_E = w_S = w_C = w_R = 0.20$	0.341	Result changes slightly
Higher admissibility emphasis	w_T=0.28, w_E= 0.28, w_S= 0.16, w_C= 0.08, w_R=0.20	0.361	Result remains in the same general range

The result indicates that the baseline outcome is not highly sensitive to modest changes in weighting but it is more sensitive to admissibility conditions and penalty intensity. A small increase in environmental and technical thresholds is enough to reduce the feasibility score to zero because the baseline values for those criteria remain close to the minimum admissibility boundary. This indicates that the pathway is not robustly feasible under the present baseline configuration. Rather, it appears conditionally credible but it is structurally vulnerable to stricter technical and environmental requirements.

The sensitivity analysis reinforces the main interpretation of the model. The pathway cannot be dismissed as scientifically implausible and nor can it be treated as strongly feasible under current screening assumptions. Its credibility heavily depends on whether the technical suitability and environmental admissibility can be maintained above minimum thresholds while the risk of impurity remains manageable.

Interpretation of Results

The model results should be read as an assessment of conditional feasibility and not as a direct implementation recommendation. In this study, feasibility score above zero indicates that the pathway is not ruled out by the model's admissibility conditions, but the strength of the result depends on how far it remains from threshold failure and how stable it is under variation.

Under the baseline configuration, the pathway remains admissible but constrained with a feasibility score of 0.351. This indicates that Singapore's waste-to-energy ash for zeolitic material synthesis cannot be treated as strongly feasible at present, also; however, it is not ruled out by the model. Hence, the baseline result is best interpreted as qualified feasibility, which means that the pathway remains scientifically plausible and potentially valuable from a circular resource perspective but it is important to note that its practical credibility is weakened by the environmental constraints, implementation distance from current Singapore practice, and impurity-related risk.

The sensitivity results sharpen this interpretation. The model remains broadly stable under modest changes in weighting, but it becomes much more fragile when the penalty intensity or admissibility thresholds are tightened. This indicates that the pathway's overall credibility depends less on how importance is distributed across the criteria and more on the pathway's ability to remain above minimum environmental and technical requirements. Hence, the results indicate the pathway appears less limited by the logic of the model than by the narrow margin within which its admissibility is maintained.

Overall, the model supports a restrained conclusion. Firstly, the pathway should neither be presented as ready for implementation nor dismissed as irrelevant. Secondly, the model identifies where further work would be most valuable. Any meaningful improvement in feasibility is likely to come from better control of impurity-related risk, stronger evidence on environmental admissibility, clearer precursor characterization, and a more developed basis for scale and cost assessment. These areas provide the most logical extension of the future work.

Seen in this way, the paper functions as a screening study rather than an endpoint. Its value lies not only in producing a baseline feasibility result but also showing which constraints matter most and where a more advanced follow up should be focussed on. A next-stage paper should be built on this model by tightening the evidence base for the most selective variables, refining the penalty structure or extending the framework into a more detailed techno-economic or application-specific assessment.

Limitations

It is a screening-level feasibility study, not an experimental synthesis study. The model does not demonstrate the formation of zeolitic materials from Singapore waste-to-energy ash, nor does it replace the need for laboratory validation, material characterization, or pilot scale testing.

The model is built from a combination of literature-grounded inputs, Singapore-specific context, and bounded screening assignments. This is appropriate for a conceptual quantitative study, but it also means that not every variable is represented by a directly observed Singapore-specific numerical value. Criteria such as scalability, cost plausibility, and circular-resource value remain partly interpretive, even when assigned within a structured and transparent framework.

The model is not fully techno-economic or engineering design tool. It does not estimate capital cost, operating cost, process yield, plant engineering requirements, or regulatory approval pathways in detail. Its narrow purpose is to assess whether the pathway appears credible enough to justify further investigation under explicit constraints.

The model simplifies several dimensions that would likely to be more complex in practice. The penalty structure combines impurity burden and related residual risk constraints into a single term and the threshold conditions are applied only to two criteria – technical suitability and environmental safety. These simplifications are useful at the screening stage, but they do not capture the details that could shape real implementation.

The study is specific to the Singapore context as represented through currently available public and research-facing evidence. Any further change in ash-management policy, treatment standards, reuse practice, or ash-characterization data could alter the feasibility picture. The present results should be read as context-bound rather than seen as something that is universally transferable.

These limitations do not invalidate the model, but they do define its proper scope. The study is best understood as a structured first-stage evaluation of pathway credibility. It should not be seen as a replacement for experimental confirmation or implementation planning.

Conclusion

The study developed a quantitative feasibility model to evaluate whether Singapore waste-to-energy ash can credibly be considered as a feedstock for zeolitic material synthesis under technical, environmental, scalability, cost, and circular-economy criteria. Instead of treating the pathway as either clearly viable or clearly unrealistic, the paper examined it as a constrained implementation question which is shaped by admissibility thresholds, impurity-related risk, and sensitivity to assumptions.

Under the baseline configuration, the model produces a feasibility score of $F = 0.351$ and does not support a strong feasibility claim. The model points to a pathway that remains scientifically plausible and potentially valuable from a circular-resource perspective. The pathway is still limited by environmental risk, distance from current Singapore practice, and weak robustness under stricter admissibility conditions. The most accurate reading of the model is that the result is qualified feasibility and not implementation ready.

The conclusion is important for two reasons. First, it suggests that the zeolitic-material route should not be dismissed within Singapore's broader ash-valorisation landscape, especially when current visible reuse remains centred on construction-related pathways such as NEWSand. Second, it shows that any stronger case for implementation would require better evidence on a small number of critical variables, particularly precursor-specific characterization, environmental admissibility, impurity management, and implementation-oriented cost and scale assessment.

The contribution of the paper lies less in the final score than in the framework it provides for judging the pathway under explicit assumptions. In that sense, the study moves the discussion from general scientific possibility to structured local evaluation.

It also provides a basis for future work. The next-stage study could replace screening-level assignments with more detailed evidence, refine the penalty and sensitivity structure, or extend the model into a more detailed techno-economic or application-specific assessment.

Overall, the result supports a restrained conclusion. The use of Singapore waste-to-energy ash for zeolitic material synthesis is not yet a robust implementation pathway. It remains a defensible candidate for future investigation as a higher-value circular materials option.

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References

1. National Environment Agency. "Solid Waste Management Infrastructure." https://www.nea.gov.sg/our-services/waste-management/waste-management-infrastructure/solid-waste-management-infrastructure

2. National Environment Agency. "Waste-to-Energy Incineration Plants." https://www.nea.gov.sg/our-services/waste-management/waste-management-infrastructure/semakau-landfill/waste-to-energy-and-incineration-plants

3. National Environmental Agency. "Provisional Environmental Standards for NEWSand^{TM}." https://www.nea.gov.sg/our-services/waste-management/provisional-environmental-standards-for-newsand

4. Nanyang Technological University. "NTU and NEA Launch Unique S$40m Waste-to-Energy Research Facility." *NTU*. Accessed 24 Apr. 2026. Available at: https://www.ntu.edu.sg/research/research-hub/ntu-and-nea-launch-unique-s40m-waste-to-energy-research-facility

5. Waste-to-Energy Research Facility (WtERF). *NTU NEWRI*. Accessed 24 Apr. 2026. Available at: https://www.ntu.edu.sg/newri/research-capabilities/waste-to-energy-research-facility-%28wte-art%29

6. National University of Singapore. "Towards a circular materials economy." *NUS News.* 7 Sep. 2018. Accessed 24 Apr. 2026. Available at: https://news.nus.edu.sg/towards-a-circular-materials-economy/

7. Ministry of National Development. "Building Sustainable, Resilient, and Liveable Cities of Tomorrow." *Ministry of National Development*. Accessed 24 Apr. 2026. Available at: https://www.mnd.gov.sg/newsroom/press-releases/view/building-sustainable-resilient-and-liveable-cities-of-tomorrow/

8. C. Vogelsang, M. Umar. "Municipal solid waste fly ash-derived zeolites as adsorbents for the recovery of nutrients and heavy metals —A review." *Water.* Vol. 15, article 3817, 2023. DOI: 10.3390/w15213817. https://www.mdpi.com/2073-4441/15/21/3817

9. Q. Zhou, X. Jiang, Q. Qiu, Y. Zhao and L. Long. "Synthesis of high-quality NaP1 zeolite from municipal solid waste incineration fly ash by microwave-assisted hydrothermal method and its adsorption capacity." *Science of the Total Environment.* Vol. 855,

article 158741, 2023. DOI: 10.1016/j.scitotenv.2022.158741. https://www.sciencedirect.com/science/article/abs/pii/S0048969722058405

10. J. Qin, Y. Zhang, S. Heberlein, G. Lisak, and Y. Yi. “Characterization and comparison of gasification and incineration fly ashes generated from municipal solid waste in Singapore.” *Waste Management.* Vol. 146, pp. 44-52, 2022. DOI: 10.1016/j.wasman.2022.04.041. https://www.sciencedirect.com/science/article/abs/pii/S0956053X22002136

11. K. S. Heng, X. Sun, A. Liu, G. Salgunan, G. Kumar, S. N. Tan. “Physicochemical characterization of Singapore’s municipal solid waste air pollution control residues and its stabilization by VKI treatment.” *International Journal of Waste Resources*. Vol. 8, no. 3, article 349, 2018. DOI: 10.4172/2252-5211.1000349. https://www.walshmedicalmedia.com/open-access/physicochemical-characterization-of-singapore8217-municipal-solid-waste-air-pollution-control-residues-and-its-stabilization-by-vk-2252-5211-1000349.pdf

12. National Environment Agency. “NEWSand: A key to Closing Singapore’s Waste Loop.” https://www.nea.gov.sg/media/news/news/index/newsand-a-key-to-closing-singapore-s-waste-loop