Absorbing shocks: Designing an agriculture vegetative waste management system resilient to final product price fluctuations

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Abstract

Purpose: What happens to a waste management system if the final product prices used to design the optimal solution turn out to be higher than real prices after implementation? We calculate the optimal vegetative management system (VWM) for the agricultural sector and its resilience to final products price fluctuations.

Methods: The research methodology is based on an economic optimization model aimed to maximize the profitability of a VWM system for the agricultural waste at the national level. We analyse the sensitivity of the optimal VWM design using a dual method to find the range of the final product price for each implemented technology under which the technology is still resilient. First, we use a risk-neutral approach to find the range of output product's prices under which each considered technology becomes the most profitable one. Next, we develop a risk-aversion measure associated to each feasible treatment technology, in order to find an additional range of final products price.

Results: The comparison between optimal design solutions, and their perceived sensitivity to final product fluctuations from different perspectives (risk-neutral and risk-aversion) allows us to design an optimal solution to the vegetative waste management system resilient to well-defined ranges of final prices fluctuations.

Conclusions: The main contribution of the paper is the development of a method of performing sensitivity analyses from risk-neutral and risk-aversion points of view applied to the design of waste management systems.

1. Introduction

Large amounts of vegetative residuals are produced annually by agriculture. These agricultural vegetative wastes are characterized by relatively expensive treatment and disposal costs. In particular, their spatial distribution makes any agricultural waste treatment scheme sensitive to the collection and transportation costs. On the other hand, the range of treatment technologies available for vegetative wastes is wide, the economic value of its outputs is potentially high, and these technologies can contribute significantly to achieve a sustainable management of biomass waste. However, the feasibility of each available technology is heavily dependent on the market price of the waste treatment final products, as biochar, charcoal, RDF (Refused Derived Fuel), heat, steam or electricity. Economic analyses of waste management systems focus generally on municipal solid waste, and rarely take into account vegetative agricultural residuals as part of their inputs (as in, for example, [25, 30]. Analyses of the economic feasibility of waste management systems for vegetative agricultural residuals, generally focus on a single treatment technology with different waste input options [4, 7, 32, 33], environmental assessment impact of specific vegetative waste treatment facility [10, 12], or a review of several waste-to-energy technologies and their associated production costs [19, 20, 34, 35]. Economic analyses which include both, waste to energy and other treatment technologies not related to energy are scarce, and generally their geographical scope is narrow [14, 16, 17].

This research is based on a holistic vegetative waste management (VWM) analysis approach, focused on the reuse of the vegetative agricultural residuals at the national level, while taking into account all potential treatment technologies (related and not related to energy production), in order to design the most profitable waste management scheme given the vegetative waste input characteristics and location. This approach is operationalized by an economic optimization model which defines not only the most profitable technology suited to each location, but also the required input capacity for each waste treatment facility. This is the waste management system design stage, in which the market price of the final product defines the expected profit of each considered technology, and therefore, influences directly the implementation choice. The optimization model operationalizes the perspective of the waste management authority regulator, a social planer aimed to maximize the social welfare, which in this case implies the maximization of the VWM profits. However, after implementation (assuming that both investment and operational costs remain stable), the overall system efficiency and, in particular, the profitability of each type of facility depends on the final product price. Once the waste management system was implemented and the designed waste treatment facilities were built, the vegetative waste treatment is constrained by the existing capabilities and costs. If the prices of the final products remain at the level forecasted during the design stage or increase, the waste management system is expected to function well. However, if prices behave erratically or drop significantly, the relative profitability of specific technologies, or that of the waste treatment system as a whole, may be compromised. In this paper, we first analyse the sensitivity of the optimal waste management design to final product prices variation in the design phase. This analysis allows us to solve the optimal design solution for each set of final product prices, defining the types of technologies to be implemented, the distribution of vegetative wastes among them, the operational costs and the final profit for each implemented treatment technology. After implementation, we assume that the costs of each technology remain stable, but the final product prices may fluctuate. The impact of these price fluctuations on the system profitability is assessed, and critical values below which chosen technologies become unprofitable are calculated. However, these critical value are relevant only if a risk-neutral perspective is adopted. If a risk-aversion perspective is adopted instead, the decision to implement a certain treatment technology or another is subject to additional considerations. The main one is the risk-aversion measure associated with each feasible treatment technology. We adopt the Arrow-Pratt approximation [28] of certainty-equivalent profits in order to compare between treatment technologies under different levels of output price fluctuations.

The paper is structured as follows: In section 2 a description of the agriculture vegetative waste economic optimization model is presented. Section 3 presents the data and the application of the model in the context of the case study. Section 4 shows the sensitivity of the optimal VWM system depending on the final prices of the waste products under the assumption of a risk-neutral perspective, and the chosen scheme in the design stage. In Section 5, a risk-aversion perspective is adopted to rank the technologies. Section 6 concludes.

2. The economic optimization model

The model objective is to search for the optimal allocation of resources for a waste management system dedicated to the treatment of vegetative agricultural waste. The following figure shows the general layout of the model:

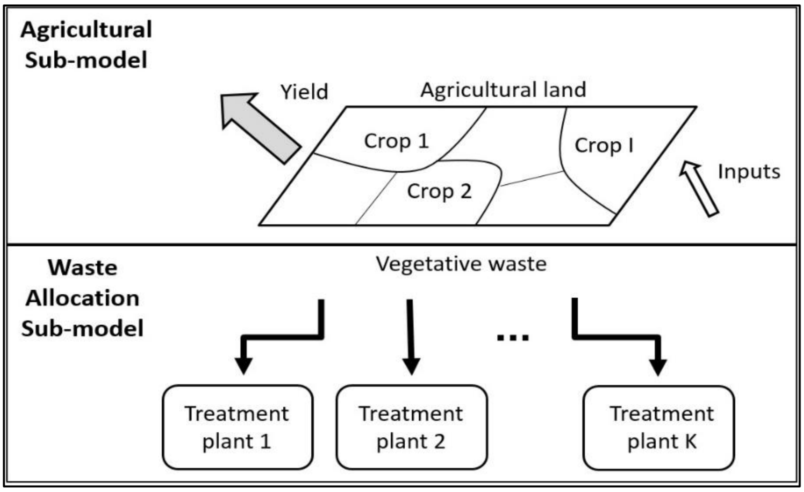

Figure 1: General layout of the agricultural waste model

Farmers cultivate crops in agricultural lands optimizing their profits by maximizing the difference between revenues (yields multiplied by market prices) and cost of inputs. As a side effect, vegetative waste is produced as well. The vegetative waste must be removed and can be used by different waste treatment technologies. Some of these technologies produce outputs not related to agricultural activity, selling their products in the market. Other waste treatment products, as compost or biochar can be used in the agricultural sector replacing fertilizers, and therefore the value of their agricultural contribution is fixed. This means that in this application the agricultural sector is viewed only as a supplier of a fixed amount of vegetative waste to the VWM.

The objective of the model is to maximize the waste management system profits, defined as following:

$$WP = WMU - WMC \quad (1)$$

Where *WP* are the total waste system profits, *WMU* represents the waste management system revenues, and *WMC* stands for waste management costs.

Three basic types of vegetative wastes from agriculture are considered: Green leaves, non-woody shrubs and field crops biomass are defined collectively as "foliage" waste. Residuals from trees, which include most orchards and forest branches and trunks are "woody" waste, and the third type is the fruits and vegetables (F&V) residuals. The specification of vegetative wastes is important since different waste treatment technologies use different vegetative input types. The model assumes that there are *J* agricultural regions in the country, each produces annually a fixed quantity of foliage, woody and F&V waste. There are *I* available vegetative waste treatment technologies, each can be implemented in any agricultural region. All three types of vegetative wastes are produced all over the country (although their quantities varies from region to region) and the treatment technologies are available everywhere. Therefore we assume that all the vegetative waste produced in region j will be treated locally. This means that there is no need to transport vegetative wastes among regions. The waste technology related data used for the analysis is included in Table 1, and the geographic-logistic data is described in Table 2.

Table 1: Waste treatment data and constraints

Name	Unit	Symbol	Comment
Input waste treatment costs	\$ / Ton	oc_i	The cost per input waste includes initial investment and operational costs
Output market price	\$ / Ton	p_i	
Foliage input	0 / 1	FO_i	1 if foliage input is allowed (otherwise 0)
Woody input	0 / 1	WO_i	1 if woody input is allowed (otherwise 0)
Fruit and vegetables input	0 / 1	FV_i	1 if F&V input is allowed (otherwise 0)

Table 2: Logistic data

Name	Unit	Symbol	Comment
Foliage waste	Ton	fo_j	Total foliage waste produced in region j
Woody waste	Ton	wo_j	Total woody waste produced in region j
Fruit & vegetable waste	Ton	fv_j	Total F&V waste produced in region j

The decision variables of the model are the following:

1- Allocation of foliage waste from region j to waste technology i (fo_{ji})

2- Allocation of woody waste from region j to waste technology i (wo_{ji})

3- Allocation of fruit and vegetable waste from region j to waste technology i (fv_{ji})

The waste management utilities are:

$$WMU = \sum_{j=1}^{J} \left(\sum_{i=1}^{I} p_i \cdot \left(fo_{ji} + wo_{ji} + fv_{ji} \right) \right) \quad (2)$$

And waste management costs are:

$$WMC = \sum_{j=1}^{J} \left(\sum_{i=1}^{I} oc_i \cdot \left(fo_{ji} + wo_{ji} + fv_{ji} \right) \right) \quad (3)$$

The objective function is then:

$$\max_{fo_{ji}, wo_{ji}, fv_{ji}} (WMU - WMC) \quad (4)$$

Subject to the following restrictions:

$$\forall i,j \;\; fo_{ji} > 0 \;\Leftrightarrow\; FO_i = 1\,; \;\; wo_{ji} > 0 \;\Leftrightarrow\; WO_i = 1 \;;\; fv_{ji} > 0 \;\Leftrightarrow\; FV_i = 1 \qquad (5)$$

$$\forall j \;\; \sum_{i=0}^{I} fo_{ji} = fo_j \;\;;\;\; \sum_{i=0}^{I} wo_{ji} = wo_j \;\;;\; \sum_{i=0}^{I} fv_{ji} = fv_j \qquad (6)$$

$$\forall i,j \;\; fo_{ji} \geq 0 \;\;;\;\; wo_{ji} \geq 0 \;;\; fv_{ji} \geq 0 \qquad (7)$$

Restriction (5) assures that the different waste types are used as inputs of technologies able to treat them only. Equations in (6) reflects the requirement that all the regional vegetative wastes are treated, and therefore the quantity of vegetative wastes produced by agriculture is equal to the quantity of inputs used by all waste facilities. Finally, (7) means that waste inputs are non-negative.

The model's task is now to optimize the VWM system, according to the objective function (4), subject to the constraints (5), (6) and (7). The result will define how the waste streams need to be allocated among the waste treatment facilities in order to achieve the maximal possible profits. This is a linear problem, and since there are no constraints on the capacities of the technologies, only one technology will be selected for each waste type from the list of technologies available for that type.

3. Case study and data

The model is applied for the case study of the agricultural sector and the VWM needs of Israel. The country is divided into 15 regional districts which produce around 1.5 M-tons of vegetative waste yearly, as described in Table 3 [17, 21]:

Table 3: The types of agricultural residuals in all districts

District	Foliage (ton/year)	Woody (ton/year)	F&V (ton/year)
North-East (1)	42,676	12,181	9,223
North East (2)	67,012	18,680	15,821
North East (3)	13,787	883	2,398
North West (1)	73,424	6,487	13,264
North West (2)	48,303	8,926	12,617
North (1)	68,389	4,109	9,127
North (2)	164,315	12,618	11,593
Center (1)	38,355	15,733	11,998
Center (2)	24,938	6,861	5,217
South West (1)	197,866	22,925	14,839
South West (2)	54,784	7,470	6,870
South East (1)	41,595	6,490	3,076
South East (2)	31,895	5,187	4,371
South (1)	284,116	39,623	18,528
South (2)	16,038	4,247	2,565
Total	1,167,463	172,421	141,509
% out of all	79%	11%	10%

Each treatment technology requires a different type of input, while some of the treatment facilities operate with only a few kinds of field crops (for example animal-feed is based on the animals' diet requirements and digestion ability). The waste treatment facilities also generate different products, which include heat and biochar for multiple purposes, charcoal for cooking, steam for industrial processes, electricity, RDF, animal food or compost. The following list includes the treatment technologies considered in the study, which were found economically feasible:

- Pyrolysis is a commonly used term describing a process of anaerobic thermo-chemical digestion of woody materials in a temperature range of 300-900 C^{o}. Its input is generally based on foliage and woody waste. The final products of the pyrolysis are heat and biochar. Biochar is a potentially high value product with a wide range of applications. Biochar can be applied as bio-sorbent of environmental contaminants in contaminated soil (for example near gas stations, industrial areas, etc.) or liquids. Biochar may also be used as a soil amendment in agricultural land allowing soil improved moisture, better nutrient absorption and pest management [1, 15, 27]. In addition, it can be used in hydroponic (no soil) crops and gardening.
- Torrefaction is a thermochemical process that, in the absence of oxygen, produces charcoal [5, 26]. The charcoal is commonly used as cooking fuel (mainly in restaurants and outdoor grill) or as biomass for electricity generation. This technology uses only woody residuals as input.
- Mixing for animal feed is a process in which vegetative residuals are added to cattle and sheep's food. Cattle and sheep's diet may include between 10-50% of agricultural residuals, in addition to their dedicated silage crops. The specific vegetative wastes used by this technology are foliage and F&V residuals [37].
- RDF production is a physical process of chopping and pressing biomass into briquettes or pellets which have a homogenous calorific value. The RDF briquettes is then used as fuel source for energy generation in industrial processes. This technology uses woody residuals or foliage as input [32].
- Composting is an aerobic process using microorganisms to produce a soil amendment. The specific vegetative wastes used by this technology are foliage and F&V residuals [29].
- Anaerobic digestion is a thermophilic process using microorganisms for biomass digestion. The vegetative inputs used by this technology are foliage and F&V residuals [31].

The following table describes which types of vegetative wastes are suitable for treatment by each of the considered treatment technologies:

Table 4: Vegetative waste treatment technologies and waste input types

Treatment technology	Foliage	Woody residuals	Fruits and vegetables
Pyrolysis for biochar	X	X	
Torrefaction for charcoal		X	
Mixing for animal feed	X		X
RDF production	X	X	
Composting	X		X
Anaerobic digestion	X		

The economic feasibility of a vegetative waste treatment facility is defined as the difference between the benefits (the market price of the produced output) and the facility costs, including both the construction costs, and the operational costs. The resulting yearly benefits, costs and profits of each considered treatment technologies are described in table 5. All the figures included in the table are given per input ton of agricultural waste.

Table 5: Yearly costs and benefits (in NIS[1]) for the different treatment facilities

Yearly costs and benefits[2]	Fixed costs	Variable costs	Fixed + variable costs	Market price of final products	Profit
Treatment facilities	(NIS per input ton of agricultural vegetative waste)				
Torrefaction for charcoal	44	80	124	420	296
Pyrolysis for biochar	169	17	185	300[3]	115
Mixing for animal feed	53	100	153	245	92
RDF production	66	130	196	272	76
Composting	62	57	119	195	76
Anaerobic digestion	37	36	73	137	64

1- *NIS – New Israeli Shekel (1 NIS ~ 0.25 € in May 2017)*

2- *The values in this table are based on academic articles as mentioned in the technologies review section, supported by internet collected data and interviews with multiple local and non-local vendors, and investors who has some kind of experience and could contribute with valuable practical information, rather than theoretical one.*

3- *The market price of biochar is a controversial issue and will be used for assessing the economic optimization model sensitivity in Section 4*

Risk-aversion associated with different waste treatments is related in our model to the assumed coefficient of variation (CV) of their final product's prices. Although CVs for prices of products produced by the technologies considered in our model are not available, we can offer a notion of CV's for other non-vegetative wastes, as glass, paper and plastic. These CVs, presented in the next table, can be compared with our simulated results in Section 5.

Table 6: Coefficient of variation (CV) of the prices for recycled glass, paper and waste in the EU during the period 2002-2013 [11]

Product	**CV**
Recycled glass	0.095
Recycled paper and board	0.201
Plastic waste	0.143

4. Risk-neutral perspective

The lack of restrictions on the location of technological solutions means that there are no economies of scale, and that the optimization model allocates all the vegetative wastes produced locally to treatment facilities located in the area. In other words, all the vegetative waste is treated locally, minimizing transportation costs. This means also that the implemented treatment technologies should be able to treat all types of vegetative waste.

Therefore, according to the results of the model under the conditions described in Table 5, all the foliage residuals (1,167,463 tons per year) will be processed in pyrolysis facilities distributed among the 15 regions. Woody waste (172,421 tons per year) will be used as input for charcoal production, and F&V residues (141,509 tons per year) will be processed by animal-feed facilities. Since the vegetative waste will be treated locally, the annual treatment capacity of the pyrolysis, torrefaction and animal-feed facilities should meet the annual vegetative waste production, as defined in Table 3.

Using the initial, "pyrolysis-dominated" waste system model result as a framework, we can analyze the sensitivity of the optimal waste management design to variations in final product prices. This is important because, assuming that the costs remain fixed, the most influential parameter in the model becomes the market price of the final products of each treatment technology. A clear example of uncertainty is the final price of biochar, the main product of the pyrolysis technology. In Israel, biochar has not yet been commercially produced, and therefore its price can only be assessed with help of experts. For example, conservative analysis defines a price range of 300 - 500 € per ton of biochar, but still, this price is potentially overrated [36]. The case of biochar is particularly dramatic given the gap between the highest and lowest estimates, but it reflects a more general feature of waste treatment and recycled products: The prices of the final products can fluctuate widely over time, based on their quality and expected use, as shown in Table 6 above. This volatility impacts directly the economic feasibility of the treatment technologies. In this context, a relevant question is: how the optimal VWM system will change if the price of an output of a dominant technology, as biochar produced by pyrolysis, varies over time? The results of the analysis are summarized in the next figure.

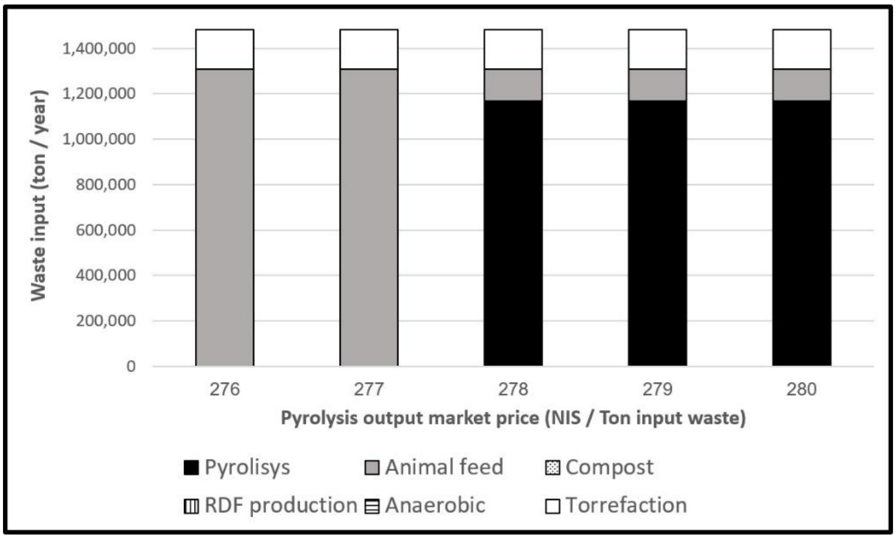

Figure 2: Sensitivity of the optimization model to pyrolysis output final prices: Transition from a "pyrolysis-dominated" to an "animal-feed-dominated" system

Figure 2 shows the optimal distribution of the annual vegetative waste among the available technologies when the pyrolysis output price, defined in the horizontal axis, varies around 280 NIS per ton input. In other words, the output price is not 300 NIS per ton, as expected according to Table 5, but much lower. If the price is above 280 NIS per ton (right section of Figure 2), the optimal waste treatment scheme is equal to the one calculated previously: Pyrolysis treating all the foliage waste, torrefaction using woody waste and animal-feed is the most convenient solution for F&V waste. If the output price drops below 278 NIS per ton, a break-event point is reached and the system becomes "animal-feed-dominated": The profit margin for pyrolysis become lower than the animal-feed's margin, and, under these conditions, the optimal waste management system is one in which all the foliage and the F&V residuals is treated by animal-feed facilities, and only woody waste is used by torrefaction.
In order to find the next break-even point, we need to assume that pyrolysis is no longer a feasible treatment option, and check the necessary conditions for a transition to a different optimal waste management system. If only five technologies (all excepting pyrolysis) compete for the vegetative waste, the next break-event point occurs when the output price of the animal-feed technology drops below the 229 NIS per input ton.

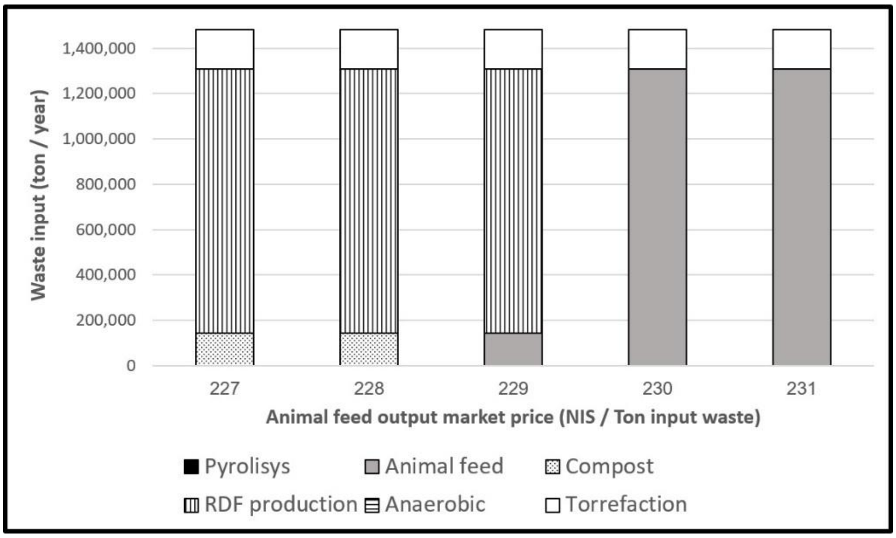

Figure 3: Sensitivity of the optimization model to animal-feed output final prices: Transition from an "animal-feed-dominated" to an "RDF-dominated" system

Figure 3 shows the optimal distribution of the annual vegetative waste among five available technologies (all excepting pyrolysis) when the animal-feed output price, defined in the horizontal axis, varies around 230 NIS per ton input. If the price is above 230 NIS per ton (right section of Figure 3), the optimal waste treatment scheme remains similar to the previous. However, at a price of 229 NIS per input ton, RDF production becomes more profitable than animal-feed, and, therefore, the foliage waste is treated using this technology. Still, all the F&V residuals are still used for animal-feed, and torrefaction continues to be the best option for woody waste. If prices of animal-feed drops a bit further, the consequence is that the technology is no longer relevant: It becomes more profitable to threat F&V residuals using for compost production. In this case the system becomes "RDF-dominated", since the foliage, the largest waste input, is treated for RDF production, and this technology coexists with torrefaction and compost.

Again, in order to discover the next break-even point, we need to assume that the only technologies considered in the next step are RDF production, compost production, anaerobic treatment and torrefaction.

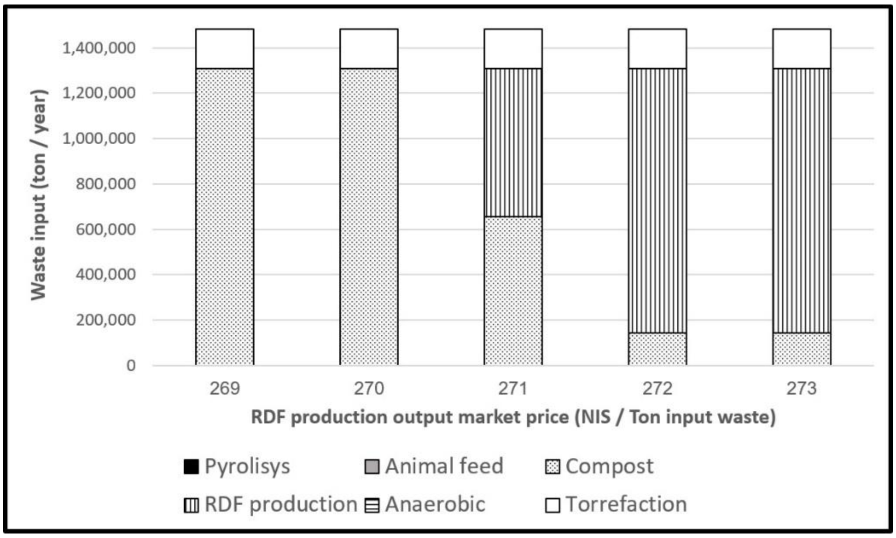

Figure 4: Sensitivity of the optimization model to RDF output final prices: Transition from a "RDF-dominated" to a "compost-dominated" system

In Figure 4, the horizontal axis is the RDF production output market price. When it drops below the 271 NIS per input ton, its competing technology, compost production, is the most profitable option both for F&V (as previously) and for foliage waste. Therefore the vegetative waste is almost completely treated by compost facilities, excepting the woody waste which continue to be treated by torrefaction. The system becomes a "compost-dominated" one. The next break-even point will be reached only when compost prices decreases enough to convert its closer competitor, anaerobic treatment, into the best option, assuming that the previously discarded technologies continue to be unavailable.

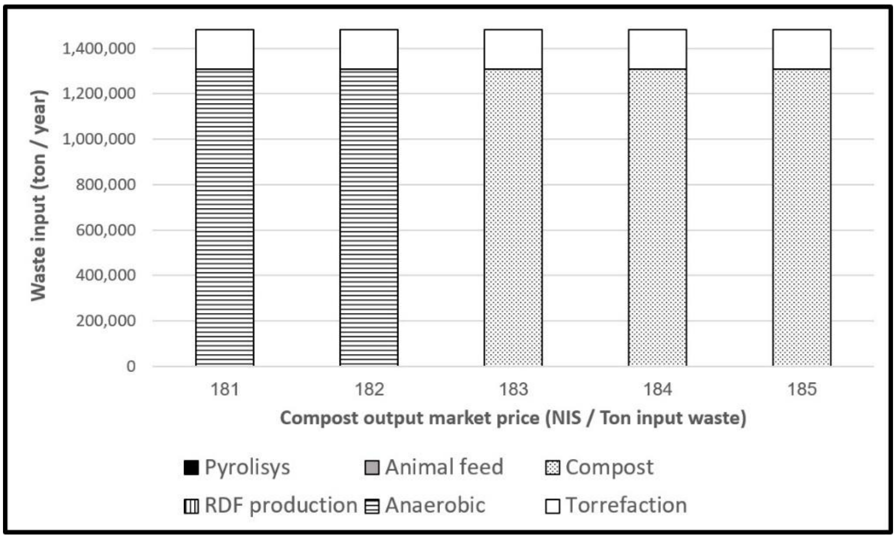

Figure 5: Sensitivity of the optimization model to compost output final prices: Transition from a "compost-dominated" to an "anaerobic-dominated" system

According to Figure 5, this happens when the compost price drops below 183 NIS per input. The competition is between composting, anaerobic treatment and torrefaction, which remains the most profitable option for woody waste. But at prices below 183 NIS, all the foliage and F&V residuals are diverted to anaerobic facilities, converting the system in an "anaerobic-dominated" one.

Along this discussion about the sensitivity of the optimal VWM system, we searched successively the minimal profit value for each technology that, below it the technology is no longer relevant and is replaced by the closest technology able to treat the same type of vegetative waste. In order to complete the picture, we go back to the original model (six technologies with values as described in table 5) and simulates changes in the charcoal price that was maintained fixed in all previous results.

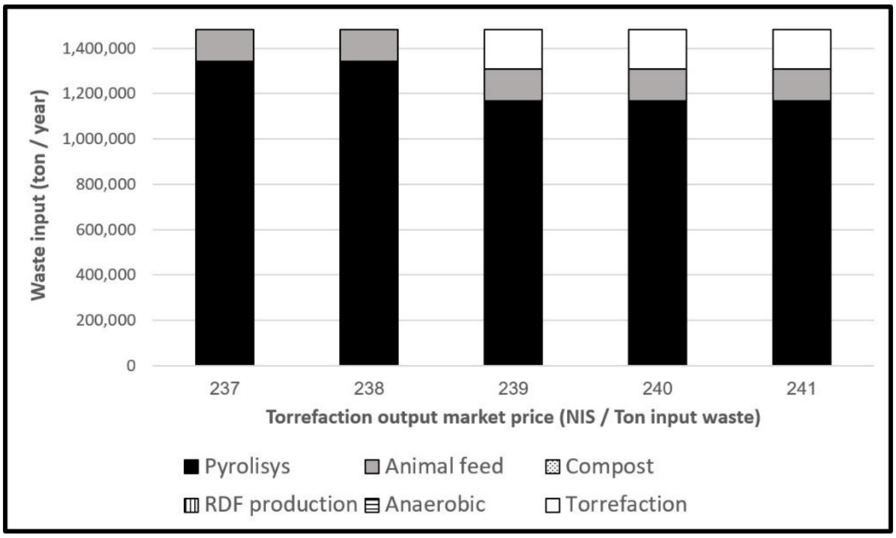

Figure 6: Sensitivity of the optimization model to torrefaction output final prices: Transition from a "pyrolysis-dominated" to a "completely-pyrolysis-dominated" system

If the charcoal (the torrefaction output) drops below 239 NIS per ton of input of woody waste, the optimal solution is to divert all the foliage and woody residuals to pyrolysis, converting the "pyrolysis-dominated" system, in one completely dominated by pyrolysis, excepting for the F&V residuals. These are not used by pyrolysis only because this type of waste is not suitable for the technology.

The conclusion of this exercise is that there are situations in which the optimization model is very sensitive to relatively small changes in its variables. As shown by Figure 2, if biochar prices in the future (after the implementation stage) will remain high (at least 278 NIS per ton), the resulting design will be "pyrolysis-dominated". But, if the biochar price is overrated and is expected to stabilize at lower levels (less than 278 NIS per ton), the designed system will not include pyrolysis at all, since it will be "animal-feed-dominated".

The next table summarizes the sensitivity of the optimal VWM to final product prices variation: Each row shows the break-even final product price of the given technology compared with the final product price of a competing technology appearing in the corresponding column.

Table 7: Summary of break-even points for pairwise treatment technologies, in NIS per input ton of agricultural vegetative waste

	Pyrolysis for biochar	**Torrefaction for charcoal**	**Mixing for animal-feed**	**RDF production**	**Composting**	**Anaerobic digestion**
Pyrolysis for biochar	**300**	481	277	262	261	249
Torrefaction for charcoal	239	**420**	216	201	200	188
Mixing for animal-feed	268	449	**245**	230	229	216
RDF production	310	491	287	**272**	271	259
Composting	234	415	211	196	**195**	183
Anaerobic digestion	188	369	166	150	149	**137**

The diagonal in Table 7 (in bold format) includes the original market price of final products as defined in Table 5. For example, the first row refers to the pyrolysis break-even final prices. The original price is 300 NIS per ton (1st column). In order to compete with torrefaction, the price needs to increase to 481 NIS per ton (2nd column). The break-even point of pyrolysis with mixing for animal-feed is 277 NIS per ton (3rd column), which is the transition to an "animal-feed-dominated" system, shown in Figure 2.

From a risk-neutral perspective, a problem arises only if, after the implementation of facilities using a specific waste treatment technology, the prices of the final products drop to a level that makes the technology unprofitable (in absolute terms, not compared with others). To this end, the data included in Table 5 is enough: If market prices of the outputs of any technology are below their fixed and variable costs per input ton, that technology is not profitable. But in that case, the possible total losses from the point of view of the whole VWM system depends on the implemented waste treatment capacities.

For example, suppose that a "pyrolysis-dominated" system was implemented, under the original assumption about pyrolysis and mixing for animal feed output market prices, as in Table 5. . This scheme implies that 1,167,463 tons of foliage waste per year will be processed in pyrolysis facilities, 172,421 tons of woody waste per year will be used as input for charcoal production and 141,509 tons per year of F&V residues will be treated by animal-feed facilities. In the unfortunate event of a simultaneous drop of the biochar market value and the mix for animal feed below their production costs (185 NIS per ton and 153 NIS per ton respectively) the VWM system is unable to treat almost 90% of its inputs. This is because only torrefaction facilities will be profitable. Both pyrolysis and animal-feed facilities will not process any inputs under these conditions. The model does not intend to assess probabilities or to forecast such price crashes, but offers a handy tool to calculate the losses faced by the different technologies in case such event happens, using equations (2) and (3) from Section 2.

5. Risk-aversion perspective

From a risk-aversion perspective, the considerations are different. It is obvious that a non-profitable technology is not worth to be implemented, but even if all the available waste treatment technologies are profitable, more subtle considerations about competing technologies and risks associated with them needs to be taken into account. Some of the technologies considered in the model, as pyrolysis, are new, and a market for its outputs (biochar) is not fully developed. Other technologies considered by the model are more established or even were implemented in small scale in Israel, but not used at a regional scale. Therefore, an entrepreneur considering implementing one of these technologies faces different levels of risks as a consequence of taking an action in the presence of uncertainty [23]. There is empirical evidence that people are generally risk averse [2, 6, 24], and that risk aversion influences processes of technology adoption [13, 22]. Also, evidences that there is a different propensity to invest on projects with technological uncertainty under risk aversion or risk neutrality assumptions are available [8, 9, 18]. However, there is a lack of empirical results about risk aversion and waste treatment technologies implementation. We adopt the Arrow-Pratt approach [28] about risk aversion coefficients and risk premiums to our analysis.

Suppose that the price of the final product of technology i fluctuate such that its expected value is p_j (as in Table 5) and the variance is σ^2. The risk premium ρ associated with technology i is defined as

$$\rho \approx \frac{1}{2} \cdot A \cdot \sigma_j^2 = \frac{1}{2} \cdot R \cdot \frac{\sigma_j^2}{{p_j}^2} \cdot p_j = \frac{1}{2} \cdot R \cdot \frac{\sigma_j^2}{p_j} \quad (8)$$

Where A and R stand for the absolute and relative risk aversion coefficients respectively, $E(p_j)$ is the expected final product price of technology i and σ^2 is the variance of the distribution. Assuming that the probability distribution is normal, the risk premium is defined by:

$$\rho \approx \frac{1}{2} \cdot R \cdot \frac{\sigma_j^2}{p_j} \quad (9)$$

The certainty equivalent profit of technology i (ce_i) is then its expected profit minus the risk premium ρ. Therefore

$$ce_j = p_j - c_j - \frac{1}{2} \cdot R \cdot \frac{\sigma_j^2}{p_j} \quad (10)$$

The optimization problem defined by equation (4) and constraints (5), (6) and (7) can be defined also in terms of certainty equivalents using equation (10). As the rank of the technologies' certainty equivalents depends on their respective variance levels σ_j^2, our sensitivty analysis with respect price variations can be implemented based on the technologies' price variences. To this end we make use of the unit less measure coefficient of variation (*cv*). Using the identity

$$cv = \frac{\sigma_j}{p_j} \rightarrow \sigma_j = p_j \cdot cv \quad (11)$$

Eq. (10) becomes

$$ce_j = p_j \cdot \left(1 - \frac{R}{2} \cdot cv^2\right) - c_j \quad (12)$$

Using (12) we are able to compare the certainty equivalent of two different technologies and, moreover, to perform a sensitivity analysis of their relative certainty equivalents under different levels of coefficient of variation.

Assume a pair of technologies *m* and *n*, where *m* has a-priori higher profitability: $(p_m - c_m) > (p_n - c_n)$. This inequality is equivalent to assume that the $cv=0$ for both technologies, according to (12), and means that under these conditions, technology *m* has a higher priority than *n*, since $ce_m > ce_n$.

In the next step we assume that still $cv_n = 0$ but $cv_m > 0$. Then, there is some $cv_{mn}^{\min}$ under which

$$ce_m(cv_{mn}^{min}) = ce_n(0) = p_n - c_n \quad (13)$$

Solving using expression (12) we get

$$cv_{mn}^{min} = \left(\frac{2}{R} \cdot \frac{p_m - c_m - (p_n - c_n)}{p_m}\right)^{0.5} \quad (14)$$

Now, assuming that both coefficients of variance are equal and positive ($cv_n = cv_m > 0$), there might be some $cv_{mn}^{\max}$ such that $ce_m\left(cv_{mn}^{\max}\right) = ce_n\left(cv_{mn}^{\max}\right)$. Using again equation (12) we receive

$$cv_{mn}^{min} = \left(\frac{2}{R} \cdot \frac{p_m - c_m - (p_n - c_n)}{p_m - p_n}\right)^{0.5} \quad (15)$$

Existence of such $cv_{mn}^{\max} > 0$ requires $p_m - p_n > c_m - c_n$. Moreover, the larger (smaller) the profit gap, expressed by $(p_m - c_m) - (p_n - c_n)$, the larger (smaller) $cv_{mn}^{\max}$.

The *cv* range $\left[0, cv_{mn}^{\min}\right)$ ensures the priority of technology *m* regardless of technology-*n*'s *cv*. If $cv_m = cv_n$, then, under the *cv* range $\left[cv_{mn}^{\min}, cv_{mn}^{\max}\right)$ the priority of technology *m* is ensured, and for $cv \geq cv_{mn}^{\max}$ technology *m* losses it's priority and technology *n* becomes the favorite.

The only parameter left to be defined in order to be able to perform the sensitivity analysis is *R*, the relative risk aversion coefficient. We use a value estimated for risk aversion as perceived by farmers in Israel [3], which is *R* = 0.611.

Figure 7 illustrates the $cv^{\min}$ & $cv^{\max}$ concept using the animal-feed and anaerobic technologies. While the animal-feed technology is more profitable, it is also associated with higher output price than that of the anaerobic method (Table 5);

in view of Eq. (12), this feature turns the CE of animal-feed more sensitive to price fluctuations. Therefore, CE of animal-feed drops with CV more sharply than that of the anaerobic method. Up to a CV level of 0.61 (cv^{min}) the animal-feed technology dominates in terms of CEs regardless of the CV associated with the price of the anaerobic technology's outputs; then, if the CVs of the two technologies are equal, their CEs break even at CV=0.92 (cv^{max}).

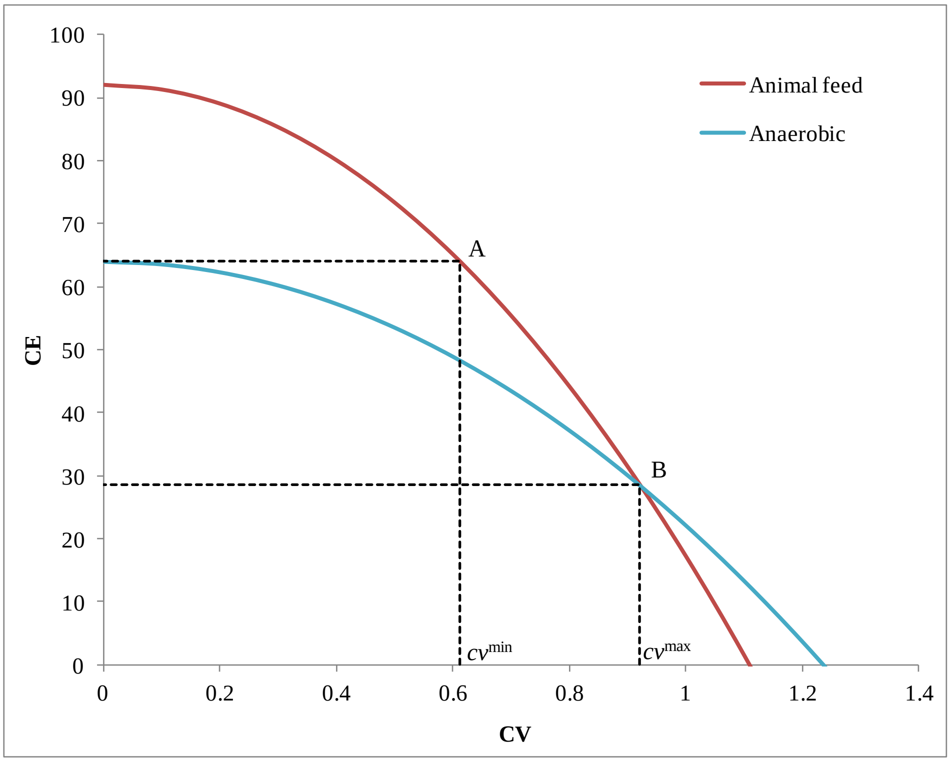

Figure 7: cv^{min} and cv^{max} for the animal-feed and anaerobic technologies

The following tables includes the comparison between pairwise waste-treatment technologies assuming final product prices and production costs as defined in Table 5. The values of cv_{mn}^{min} , cv_{mn}^{max} and their associated *ce* values were calculated according to equations (14), (15) and (12), respectively.

Table 8: Minimal levels of coefficient of variation among pairwise technologies (cv_{mn}^{min}) according to Eq. (14)

	Pyrolysis	Torrefaction	Animal-feed	RDF	Composting	Anaerobic
Pyrolysis	0	1.19				
Torrefaction		0				
Animal-feed	0.50	1.26	0			
RDF	0.64	1.31	0.45	0		
Composting	0.65	1.31	0.46	0.11	0	
Anaerobic	0.75	1.34	0.61	0.40	0.45	0

Table 9: Maximal levels of coefficient of variation among pairwise technologies ($cv_{mn}^{\max}$) according to Eq. (15)

	Pyrolysis	Torrefaction	Animal-feed	RDF	Composting	Anaerobic
Pyrolysis						
Torrefaction	2.22					
Animal-feed	1.17	1.95				
RDF	2.11	2.20				
Composting	1.10	1.79	1.02	0.21		
Anaerobic	1.01	1.64	0.92	0.56	0.82	

Table 10: Certainty equivalent of pairwise technologies calculated using $cv_{mn}^{\max}$, according to Eq. (12)

$ce(cv_{mn}^{max})$	Pyrolysis	Torrefaction	Animal-feed	RDF	Composting	Anaerobic
Pyrolysis	115					
Torrefaction	-338	296				
Animal-feed	-10	-194	92			
RDF	-292	-325		77		
Composting	4	-115	14	73	76	
Anaerobic	21	-48	28	51	36	64

Regardless of the assumed CV, torrefaction has the highest priority, a fact also reflected in the respective column in Table 10: the certainty-equivalent levels associated with the $cv_{mn}^{\max}$ of torrefaction and any other technology are all negative. Unfortunately, despite its high ranking, torrefaction only can treat woody waste which is only a small part of the total vegetative waste. For foliage waste, ppyrolysis for biochar is the favorite technology. This holds true regardless of other-technologies' CVs up to CV=0.5, the $cv^{\min}$ associated with animal-feed (Table 8). Pyrolysis loses its first rank under CV=1.01 to the anaerobic technology (Table 9), where their CE levels equate at 21 NIS/ton (Table 10). Fruits and vegetables are to be treated by the animal-feed technology, with $cv^{\min}$=0.46 and $cv^{\max}$=1.02 of that technology paired with the compost, the only other alternative.

Note that, except compost versus RDF, all the $cv^{\min}$ values reported in Table 8 exceed those reported in Table 6 for output prices of non-vegetative recycled products in the EU. This may indicate that the rank of the vegetative technologies based on risk-neutrality appraoch is expected to hold also under risk aversion appraoch.

6. Discussion and conclusions

Forecasting accurately the behaviour of future costs and prices during the design stage of any infrastructural project is a difficult task, and waste management systems are not exception. These costs and prices define the expected profit of each considered technology, and therefore, influences directly the implementation choice. After implementation, assuming that all calculated costs remain stable, the overall system profitability depends on real final product prices over time, which may fluctuate. Therefore, it is relevant to ask what will happen to a waste management system if the final product prices used to design the optimal solution turn out to be much higher than the actual prices observed in the subsequent years. In this paper we analyse the case of break-even situations in which the whole nature of the optimal VWM system changes radically, in terms of the most profitable technologies to be implemented and the distribution of waste inputs among them. First we use an economic optimization model aimed to maximize the profitability of the system, under a set of economic, technological and logistic assumptions. We perform a sensibility analysis on the final product's prices of each involved technology from a risk-neutral perspective, and found the optimal waste system that results from each defined set of prices. Using this method we are able to define what the feasibility boundaries of the final prices for each technology are, and how the designed system will change in response to price changes. However, assuming a risk-aversion perspective, the level of uncertainty associated with the final product prices of each technology is related to both the risk aversion level and the relation between prices and costs. Although there is a lack of data about risk aversion coefficients related to waste treatment technologies, we developed a method to assess the optimal waste management solution sensitivity to different assumed distributions of final product's prices. The method is based on different assumptions on the coefficient of variation of final product's prices, which in turn define risk premiums that reduces the profitability of the technologies. Certainty equivalent value is the measure of the reduced profitability in the presence of risk premiums. Analyzing the break-even points of the joint distribution of certainty equivalents and coefficient of variations, we expand the range of feasible VWM solutions. Through this exercise we link waste management economic optimization models with the literature on risk aversion and certainty equivalents. We conduct sensitivity analyses from risk-neutral and risk-aversion points of view to the design of agricultural vegetative waste-management systems. Doing so we allow additional degrees of freedom in the analysis of the optimal waste management model. If specific data about risk perception of waste treatment technologies or measures of expected fluctuations of final product outputs become available, the tools used here can be easily employed to design feasible waste management systems that cannot be calculated through optimization models based exclusively on prices and cost.

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