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Valorising Agricultural Residues into Pellets in a Sustainable Circular Bioeconomy

Waloryzacja pozostałości rolniczych na pelety w zrównoważonej biogospodarce o obiegu zamkniętym

Anders Svensson, Madelene Almarstrand, Jakob Axelsson, Miranda Nilsson, Erik Timmerman, G Venkatesh

Department of Engineering and Chemical Sciences,
Faculty of Health, Natural and Engineering Sciences, Karlstad University
E-mail (Corresponding Author): anders.sven.as@gmail.com

Abstract

It is a truism by now that the combustion of fossil fuels has execaerbated climate change, and its repercussions. Biomass in pelletised form, will emerge as substitutes, in the circular bioeconomies of the future. This brief review focuses on the utilisation of agricultural residues as raw materials for pellets, and explores the aspects of sustainability – socio-cultural, economic, environmental, and techno-functional – in the 20-plus peer-reviewed articles selected for that purpose using Scopus with a set of search-phrases. The articles are case studies dated between 2012 to 2023, tracing their provenance to different countries in the world – Brazil, Canada, China, Denmark, Greece, India, Italy, Mexico, Peru, Spain, Thailand, Türkiye, Zambia, etc. Among the many gleanings which are reported in this review, some deserve mention here in the abstract. The social aspect of sustainability has not been studied as much as the economic and environmental. The case studies emphasize the importance of adapting the pelleting process to the properties of the agricultural/horticultural residues and the prevalent local conditions. It is encouraging to note that there is a surfeit of agricultural residues (corn, coffee, quinoa, beans, oats, wheat, olives, tomatoes, pomegranates, grapes, etc. in the articles reviewed) which can be valorised to pellets, also in combination with the in-vogue forestry wastes. This is more advisable if the status quo is open burning of such residues in the fields. The journey towards the sustainable development goals (SDGs) will be aided by investments in such biorefinery-projects, SDG 17 is extremely vital for their success – collaboration and cooperation among several stakeholders around the world. This review, though based on only 20-plus articles from around the world, is an in-depth analysis which promises to be of interest to decision-makers and sustainability-specialists keen on contributing to the transition to a circular bioeconomy.

Key words: agricultural residues, biowaste, environmental sustainability, pellets, social sustainability, Sustainable Development Goals (SDGs)

Streszczenie

Truizmem jest już stwierdzenie, że spalanie paliw kopalnych zwiększyło zmiany klimatyczne i ich skutki. Biomasa w postaci granulowanej pojawi się jako substytut w przyszłych biogospodarkach o obiegu zamkniętym. Ten krótki przegląd koncentruje się na wykorzystaniu pozostałości rolniczych jako surowca do produkcji pelletu i bada aspekty zrównoważonego rozwoju – społeczno-kulturowe, ekonomiczne, środowiskowe i techno-funkcjonalne – w ponad 20 recenzowanych artykułach wybranych w tym celu przy użyciu Scopus z zestawem wyszukiwanych fraz. Artykuły stanowią studia przypadków z lat 2012–2023, pochodzące z różnych krajów świata – Brazylii, Kanady, Chin, Danii, Grecji, Indii, Włoch, Meksyku, Peru, Hiszpanii, Tajlandii, Turcji, Zambii itp. Niektóre z nich zasługują na wzmiankę w streszczeniu. Społeczny aspekt zrównoważonego rozwoju nie był badany tak często, jak ekonomiczny i środowiskowy. Studia przypadków podkreślają znaczenie dostosowania procesu granulowania do właściwości pozostałości rolniczych/ogrodniczych i panujących warunków lokalnych. Zachęcający jest fakt, że w analizowanych artykułach wskazuje się na nadmiar pozostałości rolniczych (kukurydza, kawa, komosa ryżowa, fasola, owies, pszenica, oliwki, pomidory, granaty, winogrona itp.), które można wykorzystać do postaci pelletu, również w połączeniu z odpadami leśnymi. Jest to tym bardziej wskazane, gdy dotychczasowa praktyka polega na otwartym spalaniu takich pozostałości na polach. Zmierzanie w kierunku celów zrównoważonego rozwoju (SDG) będzie wspomagane przez inwestycje w biorafinerie. Cel SDG 17 jest niezwykle istotny dla ich powodzenia – współpraca i współdziałanie pomiędzy kilkoma zainteresowanymi podmiotami na całym świecie. Przegląd ten, choć oparty na zaledwie 20 artykułach z całego świata, stanowi dogłębną analizę, która może zainteresować decydentów i specjalistów ds. zrównoważonego rozwoju, którzy chcą przyczynić się do przejścia na biogospodarkę o obiegu zamkniętym.

Słowa kluczowe: pozostałości rolnicze, bioodpady, zrównoważenie środowiskowe, pellety, zrównoważenie społeczne, Cele zrównoważonego rozwoju (SDGs

1. Introduction

A report recently published by the Intergovernmental Panel on Climate Change in 2022 (IPCC, 2022), emphasizes the urgency which is called for, in the transition from fossil-fuels to renewable substitutes. This needs to be taken seriously, if we need to restrict the rise in the global average temperature to 1.5ºC. The planned phase-out of older plants relying on fossil fuels needs to be complemented by the modernisation of the relatively-newer ones with carbon capture, utilisation and storage (CCU&S) technologies. Simultaneously, one needs to move higher up than just *harvesting the low-hanging fruit* as far as research in, development of, and investments to bring on-stream, renewable energy alternatives, are concerned.

Japhet et al. (2019), while canvassing for biomass, agree that there are some hindrances – low density, high moisture content, logistical difficulties associated with transport and storage – which can be overcome if one resorts to pelletising it. From an economic perspective, if the availability of and accessibility to residual (waste) biomass from the forestry and agricultural sectors, are guaranteed, it augurs well for investments in waste-valorising pellet-factories. In addition to deriving value from these *wastes*, one also simultaneously decreases the environmental burdens which may otherwise have to be borne – this includes the dependence on fossil fuels which aggravates climate change concerns.

In this review – which is brief from the point of view of the number of articles read and reviewed, but in-depth as far as the presentation of the gleanings therefrom are concerned – the authors propose to provide an overview of the techno-functional, environmental, economic and social aspects of sustainability (sustainable development) regarding pelletising agricultural residues. It will be of interest to decision-makers and sustainability-specialists keen on contributing to the transition to a circular bioeconomy, who will benefit from summarised knowledge about the potential of agro-residues as raw materials for pellet-production globally, as well as the challenges which need to be overcome to realise the said potential.

2. Methodology

The authors availed of the database Scopus, in the first and second weeks of November 2023. As shown in Table 1, they used different search-phrases to unearth the peer-reviewed scientific journal publications which were eventually selected for review. The two primary criteria which guided the selection were diversity of provenance (geographical) and the *recency* of publication. A good spread of different types of methodologies – interviews, numerical simulations, lab-scale experiments, environmental life-cycle analysis, social life-cycle analysis, life-cycle costing etc. – was also ensured during the selection process. The two sets of articles selected eventually by the two groups had a non-null intersection set (common elements, in other words), so to say.

3. Findings and Discussion

3.1. Techno-fucntional and process-related aspects

Process modifications (changes in existing processes) can often yield benefits – techno-functional, and thereby also economic and/or environmental. Agro-wastes from coffee plantations were the materials of interest for de Souza et al. (2019) who demonstrated that blending different raw materials to produce pellets may provide benefits in the form of greater energy density. In their Brazilian case study, they tested coffee-wastes vis-a-vis a blend of coffee and eucalyptus wastes, and arrived at the conclusion that pellets made from the latter had a higher calorific value (average of 16.8 MJ/kg) vis-à-vis the former (15.76 MJ/kg). Guo et al. (2022) likewise blended food waste with agro-residues and showed that the former can be valorised effectively into a pellet-binder. Ruiz et al (2012), in a Spanish case study, using wastes from tomato cultivation (and downstream processing in the food sector), showed that pellets made from them have a lower heating value (LHV) of 8 GJ/m^3 which is not very different from pellets made from other types of biomass.

Table 1. Summarising the search-methodology

Database	Search-phrase	Articles included in the review	Countries in the fray as case studies *(source country if different from case-study country)*
Scopus	Pellet* AND environment* impact AND *agri* residue** or *agri* waste**	• Martínez-Guido et al. (2021) • Zheng et al. (2022) • Santolini et al. (2021)	• **Mexico** • **Denmark** *(China)* • **Italy**
	Pelletizing agricultural residues AND econom*	• Kerdsuwan and Laohalidanond (2015) • Sarker et al. (2023)	• **Thailand** • **Canada**
	Pellet* AND social AND *agri* residue** or *agri* waste**	• Gannan et al (2023)	• **Zambia** *(Sweden)*
	Life cycle assessment AND *pellet fuel*	• Song et al. (2017)	• **China**
	Pellet* AND agri* AND sustaina* AND bioenergy	• Souza et al. (2019)	• **Brazil** *(Chile)*
	Agricultural AND pellet* AND economic	• Ebadian et al. (2021) • Purohit and Chaturvedi (2018)	• **Canada** • **India** *(Austria)*
	Pelletization of Agricultural Residues	• Abdulkadir and Kurklu (2022) • Alarcon et al (2017) • Duca et al (2022) • Miranda et al (2018) • Ruiz Celma (2012)	• **Türkiye** • **Peru** • **Italy** • **Spain** • **Italy**
	Agricultural pelletization LCA	• Guo et al (2022) • Li et al (2012) • Martínez-Guido et al (2021) • Santolini et al (2021) • Sarlaki et al (2021)	• **China** • **Canada** • **Mexico** • **Italy** • **China**
	Pelletization of agricultural residues LCC	• Pradhan et al (2019) • Sarker et al (2023) • Sultana et al (2010)	• **India** • **China** • **Canada**
	Pelletization of agricultural residues LCC Europe	• Karkania et al (2012)	• **Greece**

Corn wastes (cobs, stalks etc.), in Spain, as per Miranda et al (2018), account for 40% of the mass of the total output from the fields. While they can surely be incinerated for energy recovery, densifying them (pelletising in other words), results in an increase in the higher heating value (HHV). Densification, for that matter, increases the heating value of the pelleted outputs (vis-à-vis what can be recovered by conventional incineration) for all types of agro-residues (grapes and olives- Duca et al, 2022; pruning residues – Abdulkadir and Kurklu, 2022; quinoa, beans, oats etc. – Alcaron et al, 2017) – the reason simply being that it entails dewatering and drying.

3.2. Environmental aspects

All the articles focusing on the environmental dimension of sustainability have trained the lens on global warming (or emissions of greenhouse gases – GHGs – in other words). Zheng et al. (2022), in a Danish case study focusing on a combined heat and power plant (CHP) have carried out a cradle-to-gate GHG-footprint analysis to identify the hotspots along the supply chain of biomass utilised as fuel. This is a comparative environmental life-cycle analysis (E-LCA), with a functional unit of 1 MJ heat-output, which puts locally-sourced wheat straw in a favourable position (22.73 g CO_2-eq), vis-à-vis wood-pellets imported from Latvia (78.2 g CO_2-eq) and coal (117 g CO_2–eq). Wastes from corn cultivation trump coal in a study carried out by Song et al. (2017) in the Jilin province of China, by registering a reduction of 90.5% in life-cycle GHG-emissions for a given desired heat output from CHPs. Indeed, as compared to forestry wastes, availability of residues from corn cultivation is markedly seasonal, and storage thereof is a challenge to be overcome. This has been pointed out by Italian researchers in Santolini et al. (2021). This article reports an 18% reduction in GHG-emissions if pellets made from said residues are used instead of wood-pellets. On the one hand, avoiding the use of fossil-fuels is a desired end-goal. On the other hand, redirecting agro-wastes to the energy-sector instead of subjecting them to open-burning on the fields, yields additional environmental benefits by decreasing anthropogenic atmospheric pollution (Martínez-Guido et al., 2021; Song et al., 2017; Kerdsuwan and Laohalidanond, 2015; Pradhan et al, 2019). Process-optimisation, needless to say, is an area which has merited attention from researchers (Li et al, 2012; Kylili et al, 2015), as an imperative both for the quality of the pellets produced, as well as their life-cycle environmental footprint.

To reiterate, the focus by and large, has been on reduction in the net global warming impact, by replacing fossil fuels. Further analyses must also factor in other relevant environmental impacts associated with the life-cycle of the agro-residues (from field to furnace, or for that matter to other end-destinations for varying applications).

3.3. Socio-cultural aspects

Socio-cultural aspects are under-researched in general. That ought to and is bound to change in the years to come. In a very recent publication – Gannan et al (2023) – researchers from Sweden have carried out a case study focusing on the bio-energy sector in Zambia, with the lens trained on a facility producing bio-pellets. The article, which adopts the interview approach as a method for social life-cycle analysis (S-LCA), directs its attention to four stakeholder-groups in this sector – manual labourers (so-called blue-collar workers), residents in the local community, users of the pellets produced by the facility, researchers & entrepreneurs. A stark absence of gender-equality was uncovered. On a positive note, both the governments of the countries in the Southern African Development Corporation (SADC), and investors in the bio-energy sector seem to be interested in developing the bio-pellets (bio-energy in general) sector further, in a sustainable fashion, attending to any *red flags* which show up in studies such as Gannan et al (2023).

Martínez-Guido and fellow researchers from Mexico (2021), who pointed out the paradox associated with causing air pollution by *open-burning* agro-wastes in-situ, instead of valorising them as pellets for the *green* energy sector (as mentioned in sub-section 3.1), have in fact, considered all the three dimensions of sustainable development associated with the use of crop-wastes in the power sector. They have used the Human Development Index (HDI) as a metric and shown that investments in pellet-production from agro-residues are likely to contribute directly to employment generation, and thereby indirectly, to increase in household incomes, and benefits associated with health and education. Talking of health, utilisation of forestry wastes directly for cooking in poorly-ventilated kitchens, has been adversely affecting the health and well-being of women in the rural areas of developing countries. Alarcon et al (2017), in their Peruvian case study, have recommended a transition to pellets to overcome this impediment.

S-LCA can be tailormade to the challenge that needs to be overcome, or the problems that need to be solved. In other words, the stakeholder base is diverse, and often it may not be possible to please everyone equally when changes are implemented. Seeking a Pareto optimum is virtually impossible. However, this is what makes S-LCA challenging and interesting for sustainability researchers. Here is where Swiss psychologit Carl Gustav Jung's comment – *Know all the theories, master all the techniques, but as you touch a human soul, be just another human soul* – comes to mind. Theories and techniques belong to the realm of the economic, environmental and techno-functional. The social dimension calls for something more and greater.

The researchers referred to earlier in this sub-section, have considered the workers (blue-collar especially) who are at the nucleus and core of the stakeholder onion diagram with which one commences an S-LCA (Venkatesh, 2019a), as stakeholders to be prioritized. Gannan et al (2023) have pointed out that it is necessary to follow up such analyses at regular intervals by expanding the scope and size of the stakeholder groups, in order to test if there are improvements.

3.4. Economic aspects

Economic feasibility (may be termed as techno-economic, if the techno-functional aspect – sub-section 3.1 – is integrated with it) has always been the sole criterion influencing investment-related decisions, before the environmental dimension came to the fore in the 1970s. Life-cycle costing (LCC) is a common tool which is used to compare different alternatives and opt for the one with the highest net present value (NPV) and/or lowest payback time, and/or highest internal rate of return (IRR) (Venkatesh, 2019b). Costs and benefits are modelled by making suitable assumptions (simulation of an imagined reality), which can subsequently can also be varied to test their effects on the end-results (in other words, the advice provided by LCC, as regards the choice of option).

The Chinese case study by Song et al. (2017) recommends a minimum annual handling capacity of 50000 tons of wastes from corn cultivation, in CHPs, to ensure economic feasibility of replacing coal which is the default fuel choice otherwise. They, however, also encourage policymakers in China, to incentivise investments in lower handling capacities (with economic subsidies), in order to maximise the utilisation of agro-wastes, and thereby the reduction in GHG-emissions from the country's energy sector over time. One may certainly think in terms of blending agro-residues with forestry wastes, as recommended by de Souza et al (2019). In a Canadian case study, Ebadian et al. (2021) have modelled an intercontinental supply-chain for pellets produced from agro-residues in Canada and sold in Europe; and compared the same with a conventional small-scale pellet plant in Europe sourcing its biomass from the forestry sector. Production of agro-pellets, according to the authors, costs approximately 92–95 EUR/ton (a little less than the 99-109 EUR/ton for wood-pellets in Europe) but is likely to fetch a price between 183 and 204 EUR/ton on the European market, vis-à-vis wood pellets which sell at 143 EUR/ton. According to another similar study from Thailand – Kerdsuwan and Laohalidanond (2015) – the production cost of bio-pellets from corn-wastes is in the range between 49.4 and 56.8 USD/ton (equivalent to 45-52 EUR/ton). Indeed, direct comparisons between the Thai and Canadian studies are not warranted for obvious reasons.

Biomass pellets (especially the ones produced from wastes and residues), may score over fossil-fuels environmentally (and also from a social perspective, when it comes to health), but economically, as shown by Purohit and Chaturvedi (2018), power production from biomass pellets in India costs around 0.12 EUR/kWh – 20% greater than what it costs to generate electricity from cheap (subsidised) coal. In the presence of a strong coal lobby, it remains to be seen if the Indian government would like to give a fillip to the development of pellet-production from biomass-residues (which being considered as wastes will be available almost free-of-cost). If adequate policy (and thereby financial) support is forthcoming from the time of writing, and the required infrastructures are put in place, by 2030-31, biomass-pellets have the potential to account for 6% of the country's power production (Purohit and Chaturvedi, 2018). This will also go a long way in solving the air pollution issues which plague north India every year in the winter months (Pradhan et al., 2019).

Researchers from Greece, in Karkania et al. (2012), identified the importance of the capacity of the pellet-plant, electricity prices over the lifetime of the plant, energy requirements for drying the biomass, and possibilities for obtaining subsidies from the government, while making an investment decision. Sultana et al (2010), in a different case study, have pointed out that the feasibility is more sensitive to the costs incurred upstream during collection/harvesting and transportation. Pradhan et al (2019) have observed that the selling-price of pellets in the Indian market may not be steady, and a measure of confidence in the same would be imperative for investors to commit funds into such projects, or banks to lend at agreeable interest rates. By making relevant assumptions, they arrive at a possible NPV of 44096 USD and an IRR of 34%, for a small plant with a daily output of 2 tons of pellets. The aforesaid unsteadiness in the selling price makes the NPV very sensitive to it, and the authors state that a drop from 150 to 120 USD/ton would render the NPV negative and the investment infeasible. The sensitivity to selling-price has also been indicated by Sarker et al (2023), who have arrived at a minimum selling price in the range of 103-105 USD/ton, to ensure feasibility (or in other words, keep the NPV value just above zero). LCC results need to be taken with a pinch of salt, as there are uncertainties galore associated with the data incorporated into the model, and comparisons between seemingly-similar studies are also not warranted, without digging deeper into the sources of data and the assumptions made.

As Karkania et al (2012) have pointed out, selecting the right capacity is crucial for success. The 2 tons/day assumed by Pradhan et al (2012) is equivalent to about 730 tons per year – a tiny-small scale plant, if one may say so. The optimal capacity recommended by Sultana et al. (2010) is 70,000 tons per year. The adoption of suitable pre-treatment techniques plays an important role in holding down the production expenses. A delicate balance between the technological factors that determine the quality of pellets (higher quality can fetch a higher price on the market) and the associated economic factors that determine the NPV, IRR and thereby the feasibility, is called for.

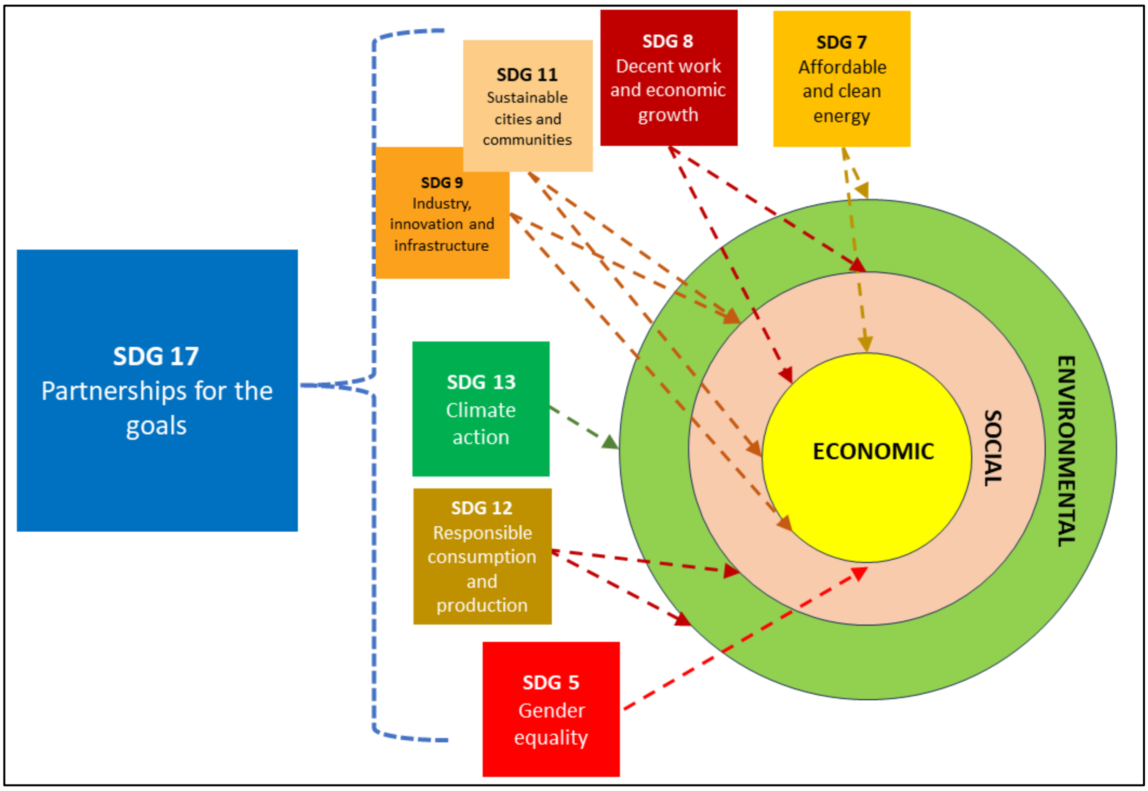

Figure 1. The SDGs associated with the findings from the articles reviewed, source: done by the authors solely for this paper)

4. Conclusions and Recommendations

The authors embarked upon a short but focussed review of peer-reviewed journal publications focusing on different aspects of sustainability – techno-functional, environmental, economic and socio-cultural – of the potential of agro-residues as raw materials for production of pellets, with complete awareness of the fact that the intention was never to write a comprehensive review. It is a known fact that all countries of the world are not equally endowed with forests and thereby access to residues from the forestry sector. This necessitates innovation and subsequent investments in infrastructures, in order to tide over this disadvantage and look towards agriculture/horticulture/floriculture.

While the primary driver behind replacing fossil fuels with pellets produced from agro-residues is combating climate change (SDG 13), setting in motion strategies and plans (SDG 9) to harness the potential that exists at the confluence of solid waste management (SDG 11) and renewable energy (SDG 7), will influence a host of other SDGs (three of which have already been referred to, within parentheses). If employment opportunities are created in this bio-energy sub-sector, women must not be under-represented in it (SDG 5). All in all, investing in pellet-production plants availing of cheap agro-residues, will open up decent work opportunities all along the value chain (from the field to the furnace, so to say) – SDG 8. However, any rebound effect must be avoided by emphasizing SDG 12; just because the pellets are produced form agro-residues, does not mean that wasteful consumption can be permitted. In order to ensure that everything works in clockwork precision, SDG 17, which builds, nurtures and sustains long-term partnerships, must not be forgotten. Literally, it is the last but by no means the least!

Let’s finish with our recommendations:

1. Agro-residues which have traditionally been considered as wastes are to be necessarily looked upon as resources in a circular bioeconomy (Japhet et al, 2019), especially in regions where access to, and availability of forestry wastes are limited (Ebadian et al., 2021; Sarker et al, 2023)
2. Utilisation of agro-residues for pellet production instead of open-burning in fields, contributes to a host of sustainable development goals – SDG 7, SDG 8, SDG 9, SDG 11, SDG 12 and SDG 13.
3. Research into other potential uses for agro-residues in bio-refineries must gain traction and momentum in the years to come, in universities (Sarlaki et al, 2022).
4. Social sustainability issues need to be brought to the forefront, and must be given as much importance as is now being accorded to the environmental and economic dimensions of sustainability (Gannan et al, 2023; Ebadian et al, 2021).
5. Environmental life-cycle analyses must factor in impacts other than just global warming which happens to attract attention by default these days.
6. Venture capital sans the self-serving short-termism is called for.
7. Disruptive innovation is not always needed; stepwise process modifications uncover economic and environmental benefits, in addition to improvements in productivity and product-quality.

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