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Review article

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Present status (PS) of integrated bio refineries (IBRs) and sustainable development engineering (SDE) together with editorial of future research (FR) for multi-disciplinary (MD), multi-scales (MSs), multi-plat-forms (MPFs), multi renewable raw materials (MRRMs) feed-stocks (FSs) IBR for SDE

Abstract

SDE is more advanced than Environmental Engineering (EE), the best way to analyze their relations is by using the System Theory (ST) especially the Integrated System Approach (ISA) which from a certain point of view shows EE as a subsystem of SDE with the other most important sub-system being RRMs.

From another point of view SDE can be considered a subsystem of Sustainable Development (SD), with the other sub-systems being the other sustainability sub-systems, e.g.: SD-economics; SD-politics; SD-sociology; SD-production; SD-consumption; SD-ethics; etc.

IBRs are the most important sub-systems of SDE especially with regards to production from MRRMs. This Editorial Paper (EP) introduces PS IBRs and the future ones with large number of MRRM FSs and larger number MPFs.

Keywords: renewable raw materials, multiple RRMS, integrated bio refineries, feed stocks, bio fuels, bio products, bio energies, global warming, multi-dimensional, multi cross disciplinary, carbon nano tubes, lignocellulose, lignin, lipid, microalgae, carbohydrates, biomass conversion, environmental engineering, sustainable development, SD engineering, CO_2 emission, CO_2 sequestration, trans-esterification, photo bio reactors, biotechnology, nanotechnology, bioethanol, biodiesel, fermentation, membrane fermenters, valorization, de-valorization

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Abbreviations: RRMs, renewable raw materials; MRRMs, multiple RRMS; IBRs, integrated bio refineries; FSs, feed stocks; BFs, bio fuels; BPs, bio products; BEs, bio energies; GW, global warming; MD, multi-dimensional; MCD, multi cross disciplinary; CNTs, carbon nano tubes; BC, biomass conversion; EE, environmental engineering; SD, sustainable development; SDE, SD engineering; MFs, membrane fermenters

Introduction

This EP addresses in an integrated manner, the development of IBRs, SD and their relation to each other. With special emphasis on the use of RRMs to achieve SD and not only a clean environment. The article addresses all distinction between Environmental Engineering (EE) and Sustainable Development Engineering (SDE).

Many parts address the MRRMs and their choice as well as the suitable enzymes and microorganisms to be used.

The heart of the paper and most of its parts will address the challenges of moving from the present two platforms and one RRM to the complex novel ones with MPFs and MRRMs FSs. It presents the advancement towards MD IBRs with a variety of products, e.g.: BFs, BPs, Bio-polymers and Bio-medicine from a wide range of MRRMs. It addresses EE and SDE using simple IBRs with two PFs as well as complex ones with MRRMs FSs and large number of PFs producing a wide range of BFs and BPs including Carbon Nano Tubes (CNTs) from lignin extracted from lignocellulose waste materials, as well as Bio-Energies (BEs). The treatment of wide range of MRRMs to produce a wide range of BFs; BPs and BEs will fight pollution, Global Warming (GW) and CO_2 emission, etc.

SD is formed of a large number of subsystems such as the engineering one (SDE), economical ones, etc. Therefore, the subject is MD by its very nature. This EP concentrates on SDE which, from a ST point of view, can be formed of the two subsystems: EE and MRRMs.[1–5] From a Non-linear Dynamics (NLDs) point of view, especially stability theorem, it can be divided into necessary but not sufficient condition which, in the process industry, is namely: Maximum Production Minimum Pollution (MPMP), what makes this necessary condition, sufficient is the introduction of RRM for simple IBRs and MRRMs for the complex MD MPFs IBRs.[6] A relatively simpler analysis of these complex IBRs has been presented earlier.[7,8]

IBRs are the most important integrated tools to achieve SD with regard to BFs and BPs, particularly when using MRRMs. The PS IBRs process biomass fed through two platforms, one biochemical and the other thermal; the single platform is not an IBR but an Elementary Bio-Refinery (EBR).[9] However, IBRs still require extensive development with regards to its configuration, the optimization of each unit, and the overall efficiency of the processes. What's more, two platforms IBRs are not the end of the story; more platforms using different kinds of biomass waste, energy crops, or microalgae (natural and synthetically produced from photo-bioreactors using CO_2 as feedstock) are possible. These multi-platforms IBRs have the potential to drastically increase the CO_2 consumption of IBRs by utilizing natural and industrially generated CO_2. They also expand the range of raw materials that can be employed, for example agricultural wastes such as rice, wheat straw, cotton stacks, and corn Stover (which are mainly lingo-cellulose) also energy crops such as switch grass (which is mainly lingo-cellulose) and Jatropha (which is a mixture of lingo-cellulose and lipid) can be used. In addition to algae (natural and produced from CO_2 in photo bioreactors) that can also be used.

IBRs and this suggested MD IBRs are becoming most important after nature did ring the bell of anger during this destructive wave of Global Warming (GM) which is a negative subsystem of the neglect of SD.

Goals and discussion

This editorial paper addresses IBRs both in the PS and future novel developments. A specific focus is on the application of MRRMs in IBRs of different degrees of complexity and sophistication with regard to the configuration, ensuring sustainability by replacing non-RRMs by RRMs. When the raw material is changed, it is typically accompanied by a change in technology, and this opens the door for advanced research using Mathematical Modeling (MM), Computer Simulation (CS) and Experimental Verification (EV) to integrate chemical processes with biochemical techniques to achieve the optimal synergy of the two or more platforms IBRs, this will also involve the use of novel technologies such as membrane reactors.[6–9] The overall aim is to be able to produce a wide range of BFs and BPs from a wide range of MRRMs in MPFs IBR using novel technologies. The analysis of an IBR includes that of its optimal configuration, simple process optimization using Mass and Heat Balances (MHBs), and more advanced optimization using MM, CS, EV and Computational Fluid Dynamics (CFD) techniques in a unified manner (e.g.: physico-chemical or empirical models are created and then their accuracy is improved in a feedback loop with experimental data). Such optimization for each RRM is essential to achieve maximum efficiency of the particular IBR, while at the same time providing flexibility to convert any feedstock into power, heat and value-added products (BFs, BPs) in a sustainable manner. In addition, each subsystem of each platform is investigated and optimized with regard to its configuration, optimal design and optimal mode of operation taking into consideration modern findings in both sides, e.g.: membrane reactors and bio-reactors, integrated auto-thermic reactors, exploration of the implications of bifurcation and chaos in autonomous and non-autonomous systems, etc.[10,11]

Many articles and review ones discuss the different approaches for dealing with IBRs, especially with regard to the use of novel technologies, e.g.: membrane catalytic and bio-catalytic reactors, in addition to other challenges associated with BFs, BPs and BEs from RRMs as well as other sides of IBRs.[12–20]

In addition to the above, the number of platforms can be increased with increasing the number of BPs using the same non-edible MRRMS. For example, additional platforms can be added by using the same MRRMs biomass to produce Bio-polymers and Bio-medicines[21,22] from the same MRRMs, we will start in this article by 3 Bio-polymers and 3 Biomedicines. Therefore additional 6 platforms are added per one RRM. In addition, the main biochemical platform used to produce BFs/BPs from the lingo-cellulosic non-edible RRM biomass, the first step is the delignification of lingo-cellulose to separate lignin in one side from cellulose-hemicellulose in the other side. The present state is that lignin is completely used to produce energy and electricity for the process and they are more than what is needed by the process and extra electricity is sold. What is suggested in this EP is to create an additional platform to process the extra lignin to produce Carbon Nanto Tubes (CNTs) in a special Fluidized bed with Chemical Vapor Deposition (CVD) catalyst.[23–27] The thermal platform can be made into 2 one is the usual gasification to syngas after conditioning is reacted in Fischer Tropsch reactors to produce BFs and BPs. The second is pyrolysis to produce bio-oil which is cracked in a Fluid Catalytic Cracking (FCC) unit to produce a range of BFs. Therefore, according to the above the total number of platforms per RRM of the first 4 RRMs is 10 PFs. For the other 3 RRMs (i.e.: Jatropha and Algae) PFs=11 per RRM taking into consideration a PF for separation of lipid and transforming it to biodiesel. Therefore for this MD, MSs, MPFs, MRRMs FSs for SDE with 4 standard MRRMs Lignocellulose biomass + one Jatropha and 2 algae the total number of PFs is =4X10+3X11= 73 PFs for this MD IBR. For PS IBR with one RRM FS the total number of PFs is 2; the IBRs in between are given in Table 1 below.

Table 1 Numbers of PFs for different types of MD, MSs, MRRMs FSs for SDE

Type of IBR	Total no. of MRRMs, NT=NLGC+ NJA	No. of Lignocellulose, (LGC) MRRMs , NLGC	No. of Jatropha and Algae MRRMs, NJA	No. of Platforms: NPFs=NLGC*10 +NJA*11 Except for the PS simple IBRs with NT=1, NPFs=2
1	1	1	0	2
7	7	4	3	73
2	2	2	0	20
3	3	3	0	30
4	4	4	0	40
5	5	4	1	51
6	6	4	2	62
8 Additional example 1 (e.g.1)	8	5	3	83
e.g.2	9	5	4	94
e.g. 3	11	6	5	115

Applying material balances in a simplified systematic approach[28] is shown below in sequential description then summarized in Table 2, The lignin L_i can be divided into two parts for each i =1-7 as shown below. The fraction of L_i to be transformed to Benzene is B_i and the rest is transformed to CNTs. The choice of the B_i values depends upon economics and market conditions.

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I. Biomasses, i=1-4, the following sequence of relations valid for all 4 first RRM, not for Jatropha and the 2 types of algae:

1) Lignocellulose in any $RRM_i \equiv LC_i$, i=1-4
2) Lignin in all RRMs except $\equiv L_i$, i=1-4
3) $x_i = L_i / LC_i$ (LC_i is RRM_i)$\rightarrow L_i = x_i. LC_i$, i=1-4
4) Carbon Nano Tubes from different $L_i \equiv CNTs_i$, i=1-4
5) $a_i = CNTs_i / L_i \rightarrow CNTs_i = a_i. L_i = a_i. X_i. LC_i$ (LC_i is RRM_i) , i=1-4
6) $B_i \equiv$ fraction of L_i used to produce Benzene ($C_6 H_6$)

II. Jatropha i=5:

1) (Ligno-cellulose, LC_5)/ (total Jatropha, LC_{T5} (which is RRM_5)) $=y_5 \rightarrow LC_5 = y_5. LC_{T5} = y_5. RRM_5$
2) Lignocellulose in any Jatropha $\equiv LC_5$
3) Lignin in lignocellulose of Jatropha $\equiv L_5$
4) $x_5 = L_5 / LC_5 \rightarrow L_5 = x_5. LC_5$
5) Carbon Nano Tubes from $L_5 \equiv CNTS_5$
6) $a_5 = CNTs_5 / L_5 \rightarrow CNTs_5 = a_5. L_5 = a_5. x_5. LC_5$
7) $B_5 \equiv$ fraction of L_i used to produce Benzene ($C_6 H_6$)

III. Algae (natural):

1) Lignocellulose in natural algae $\equiv LC_6$
2) (Lignocellulose in natural algae, LC_6)/ (total natural algae, LC_{T6} (which is RRM_6)) $=y_6 \rightarrow LC_6 = y_6. LCT_6 = y_6. RRM_6$
3) Lignin in lignocellulose of natural algae $\equiv L_6$
4) $x_6 = L_6 / LC_6 \rightarrow L_6 = x_6. LC_6$
5) Carbon Nano Tubes from $L_6 \equiv CNTS_6$
6) $a_6 = CNTs_6 / L_6 \rightarrow CNTs_6 = a_6. L_6 = a_6. x_6. LC_6$
7) $B_6 \equiv$ fraction of Li used to produce Benzene ($C_6 H_6$)
8) Approximate estimate of Lipid in Algae, $LP_6 = (1-y_6). LCT_6 = LP_6 = (1-y_6). RRM_6$

IV. Algae, synthetic, e.g., in a photo-bioreactor with CO_2 feed:

1) Lignocellulose in synthetic algae, e.g., in a photo-bioreactor with CO_2 feed $\equiv LC_7$
2) Lignocellulose in synthetic algae, LC_7)/ (total synthetic algae, LCT_7 (which is RRM_7)) $=y_7 \rightarrow LC_7 = y_7. LCT_7 = y_7. RRM_7$
3) Lignin in lignocellulose of natural algae $\equiv L_7$
4) $x_7 = L_7 / LC_7 \rightarrow L_7 = x_7. LC_7$
5) Carbon Nano Tubes from $L_7 \equiv CNTs_7$
6) $a_7 = CNTs_7 / L_7 \rightarrow CNTs_7 = a_7. L_7 = a_7. x_7$. LC7
7) $B_7 \equiv$ Benzene ($C_6 H_6$) from $L_7 = L_7 - (a_7. x_7. LC_7) = (x_7. LC_7) - (a_7. x_7. LC_7) = (1- a_7). (x_7. LC_7)$
8) Approximate estimate of Lipid in Algae, $LP_{7=} (1-y_7). LCT_7 = (1-y_7). RRM_7$
9) Approximate estimate of CO_2 consumed per ton Algae produced $\equiv Y_{CDOtoA}$
10) CO_2 consumption $= Y_{CDOtoA}. LCT_7 = Y_{CDOtoA}. RRM_7$

This benzene above is reacted with a part z of the bioethanol resulting from the cellulose –hemicellulose in the above 7 steams = $B= (B_1+B_2+B_3+B_4+B_5+B_6 +B_7). z = z. \sum_{1}^{7} Bi$, This Benzene if produced from certain fractions of L_i will be reacted with Bioethanol produced from the biochemical platform to produce Ethyl Benzene (EB) which is then dehydrogenated to Styrene and then polymerized to Polystyrene used in the foam industry. Most efficient modern efficient processes should be used, e.g.: relatively advanced process for dehydrogenation of EB to styrene is the catalytic process with hydrogen selective membranes to beak the thermodynamic equilibrium barrier of this reversible reaction and also producing pure hydrogen as a secondary product (Table 2).[29]

Table 2 Of the state variables, physical, design and optimization parameters

	RRM_i Renewable raw material. tons/day	**LC_i, Ligno-cellulose**	**LP_i, Lipid**	**LC_i+LP_i**	**x_i=L_i/ LC_i =fraction Lignin in Ligno-cellulose**	**L_i, Lignin= x_i. LC_i**	**Cellulose-Hemicellulose CHC_i= LC_i- L_i**	**Carbon Nano Tubes $CNTs_i$, tons/ day**	**a_i= $CNTs_i$/ L_i, fraction of CNTs to Lignin production ratio**	**y_i= fraction LC_i / RRM_i**	**B_i, fraction of L_i made into C_6H_6**
Biomass 1	RRM_1	LC_1= RRM_1	LP_1=0	LC_1=RRM_1	L_1/LC_1	L_1 =x_1.LC_1	CHC_1= LC_1- L_1	$CNTs_1$	$CNTs_1$/L_1	1	B_1
Biomass 2	RRM_2	LC_2= RRM_2	LP_2=0	LC_2=RRM_2	L_2/LC_2	L_2 =x_2.LC_2	CHC_2= LC_2- L_2	$CNTs_2$	$CNTs_2$/L_2	1	B_2
Biomass 3	RRM_3	LC_3= RRM_3	LP_3=0	LC_3=RRM_3	L_3/LC_3	L_3= x_3.LC_3	CHC_3= LC_3- L_3	$CNTs_3$	$CNTs_3$/L_3	1	B_3
Biomass 4	RRM_4	LC_4= RRM_4	LP_4=0	LC_4 =RRM_4	L_4/LC_4	L_4 = x_4.LC_4	CHC_4= LC_4- L_4	$CNTs_4$	$CNTs_4$/L_4	1	B_4
Jatropha	RRM_5	LC_5= y_5. RRM_5	LP_5= (1- y_5). RRM_5	LC_5+LP_5	L_5/LC_5	L_5= x_5.LC_5	CHC_5= LC_5- L_5	$CNTs_5$	$CNTs_5$/L_5	LC_5/ RRM_5	B_5
Natural Algae	RRM_6	LC_6= y_6. RRM_6	LP_6= (1- y_6). RRM_6	LC_6+LP_6	L_6/LC_6	L_6= x_6. LC_6	CHC_6= LC_6- L_6	$CNTs_6$	$CNTs_6$/L_6	LC_6/ RRM_6	B_6
Synthetic Algae	RRM_7	LC_7= y_7. RRM_7	LP_7= (1- y_7). RRM_7	LC_7+LP_7	L_7/LC_7	L_7= x_6. LC_6	CHC_7= LC_7- L_7	$CNTs_7$	$CNTs_7$/L_7	LC_7/ RRM_7	B_7

CNTs: Molecular Formula of Lignin: $C_{18}H_{13}N_3Na_2O_8S_2$, i.e.: 1 mole of L_i gives 18 moles of C. Molecular weight of Lignin= 509.4, i.e.: 509.4 gm lignin will give 18 X12= 216 gm Carbon, 1 gm Lignin = 216/509 = 0.424 gm Carbon. Thus, the values of a_i based on 100% conversion (X_{conv} =1.0) =0.35-0.45 depending on the type of L_i and type of $CNTs_i$. The actual conversion X_{act} will depend on the State of the Art (SA) of the design and optimization of Fluidized Bed Reactor with Chemical Vapor Deposition (CVD) Catalyst for converting L_i

to $CNTs_i$. The SA may allow X_{act} = 0.4-0.5. Further research using kinetics model as well as reactors modeling, experimental verification and will increase X_{act} considerably.[30]

B_i: These are the values of the fraction of fraction of L_i to be used to produce C_6H_6 and are arbitrary depending upon economics and market conditions.

CO_2 consumption for synthetic algae: Consumption of CO_2 emitted which contributes positively against

$$GW = Y_{CDOtoA}.\ LCT_7 = Y_{CDOtoA}.\ RRM_7$$

x_i and y_i: The x_i, which is the fraction of lignin in the lignocellulose, vary depending on the type of biomass, its strain and whether the lignocellulose is almost the whole biomass i=1-4, or it is part of Jatropha or algae, i=5-6. It varies in the range ~ 0.15- 0.30 for i=1-4,[31] for i=5-7 it varies in the range ~ 0.15-0.20.[32] For i=1-4, which are free of the lipid y_i, which is the fraction of lignocellulose =1.0 and for i= 5-7 it varies widely in the range ~ 0.25-0.55 depending on the strain of Jatropha and the natural or synthetic (e.g.: in photo bioreactors) algae.[33–36]

This EP is very useful in introducing the audience to the present 2 platforms and one biomass RRM FS and it also introduces the audience to the novel complex MFSs with MPFs IBRs with multi platforms and multiple RRMs feedstock in order to achieve SD, reduction of CO_2 emission and other environmental and economic benefits.

Most papers published are dealing with 2 platforms and one RRM feedstock. This EP will deal with large number of platforms with a large number of MRRMs FSs.

This EP is a clear illustration of the preliminary steps towards the development of Novel(N) Complex(C) IBRs for SD (NCIBRS for SD), to be followed by other steps. It does not only illustrate the use of a wide range of biomasses wastes and algae to produce a wide range of BFs, BPs and BEs that is very useful but it also achieves controllability of CO_2 emission and GW that is beneficial for the earth and its inhabitants. Both aspects are very useful for SD. This stage involves MBs followed by HBs both described by Algebraic Equations (AEs). Followed by the Design Stage (DS) characterized by equations of the types: AEs and Ordinary Differential Equations (ODEs) and Partial Differential Equations (PDEs) for Mass, Heat and Momentum. This stage involves 3 experimental substages:[37–39]

1. Gathering rate equations and their parameters for rate processes as well as thermodynamic equilibrium. These can be obtained from the literature, when available, or from own experiments.
2. Parameter estimation for verification of all above balances and designs equations against laboratory, pilot plant and commercial (if available) results to ensure the validity of equations for balances and designs calculations.
3. Use the above verified equations for sensitivity analysis and optimization for each unit and the entire NCIBR for SD.

Future advanced work will involve the above for dynamic investigation, Direct Digital Control (DDC) and the use of Artificial Intelligence (AI).

As a final comment it should be noticed that many equipment of this NCIBR for SD are affected positively/negatively by static and dynamic bifurcation as well as chaotic behavior. These phenomena should be exploited when their effects are positive and controlled when their effects are negative.[40]

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Conflicts of interest

The authors declare that there are no conflicts of interest.

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