Environmental Industry Letters
https://journals.tultech.eu/index.php/eil
ISSN: 2806-2965
Volume 2, Issue 1
DOI: https://doi.org/10.15157/eil.2024.2.1.30-43
Received: 30.01.2024; Revised: 06.03.2024; Accepted: 20.03.2024

Research Article

Modeling the Circular Economy in Cellulose Synthesis from Recycled Materials: A Novel Construction Management Approach

Reza Yeganeh Khaksar[1]*
[1]Department of Civil Engineering, Sadjad University, Mashhad, Iran
* **rezayeganeh@sadjad.ac.ir**

Abstract

The adoption of circular economy principles is paramount to the sustainable transformation of cellulose production. The circular economy emphasizes the continuous use and recycling of materials, reducing waste and environmental impact. In cellulose production, incorporating recycled materials minimizes the demand for virgin resources, conserves energy, and mitigates environmental degradation. By embracing circularity, the cellulose industry contributes to resource efficiency, lowers its carbon footprint, and aligns with global sustainability goals, fostering a more resilient and eco-friendly production model. The present study developed a circular economy-based model as per recycled materials for the production of cellulose with the application of MATLAB 2019b software. In the created model, kinetic equations for cellulose synthesis are applied. As well, a sensitive analysis is done due to the behavior of the presented sustainable system during that time.

Keywords: Cellulose production; Circular economy; Recycled materials; MATLAB software.

INTRODUCTION

In the pursuit of sustainable and eco-friendly practices, the production of cellulose from recycled materials has emerged as a promising avenue. Cellulose, a fundamental component of plant cell walls, is a versatile biopolymer with applications ranging from paper and textiles to biofuels and medical products. Harnessing the potential of recycled materials for cellulose production not only addresses environmental concerns but also contributes to a circular economy. This passage explores the key aspects of sustainable cellulose production from recycled materials, highlighting its environmental benefits and potential applications [1–3]. Traditional cellulose production often relies on virgin plant sources, leading to deforestation and increased environmental impact. Shifting towards recycled materials as a resource for cellulose production offers a more sustainable alternative. Commonly used recycled materials include post-consumer paper waste, agricultural residues, and even textile waste. By repurposing these materials, we reduce the demand for new resources, decrease waste in landfills, and mitigate the environmental footprint associated with cellulose production [3–5].

Sustainable cellulose production from recycled materials offers several environmental benefits. Firstly, it helps conserve forests by decreasing the reliance on wood-derived cellulose. Additionally, recycling materials significantly reduces energy consumption and carbon emissions compared to the conventional manufacturing processes involved in cellulose production. This eco-friendly approach aligns with global efforts to combat climate change and promotes responsible resource management [6].

The concept of a circular economy emphasizes the importance of closing the loop in material lifecycles. Utilizing recycled materials for cellulose production aligns with this principle by transforming waste into a valuable resource. As we repurpose materials that would otherwise end up in landfills, we contribute to a more sustainable and efficient use of resources. This not only reduces the environmental impact but also fosters economic resilience through the creation of new value chains centered around recycling [7–9]. Sustainable cellulose derived from recycled materials finds applications across various industries. In the paper and textile sectors, recycled cellulose can be used to produce high-quality, environmentally friendly products. Moreover, advancements in technology enable the development of bio-based materials, such as bioplastics and nanocellulose, opening up new possibilities in the fields of packaging, medicine, and electronics [10]. The illustration in Figure 1 depicts the market value of cellulose fiber in the United States across various applications, spanning the period from 2014 to 2025 and denominated in billion U.S. dollars. This data underscores the significance of cellulose production, emphasizing the potential advantages that can be derived from adopting sustainable practices, particularly those aligned with a circular economy. Such approaches have the potential to yield substantial benefits for communities worldwide [11].

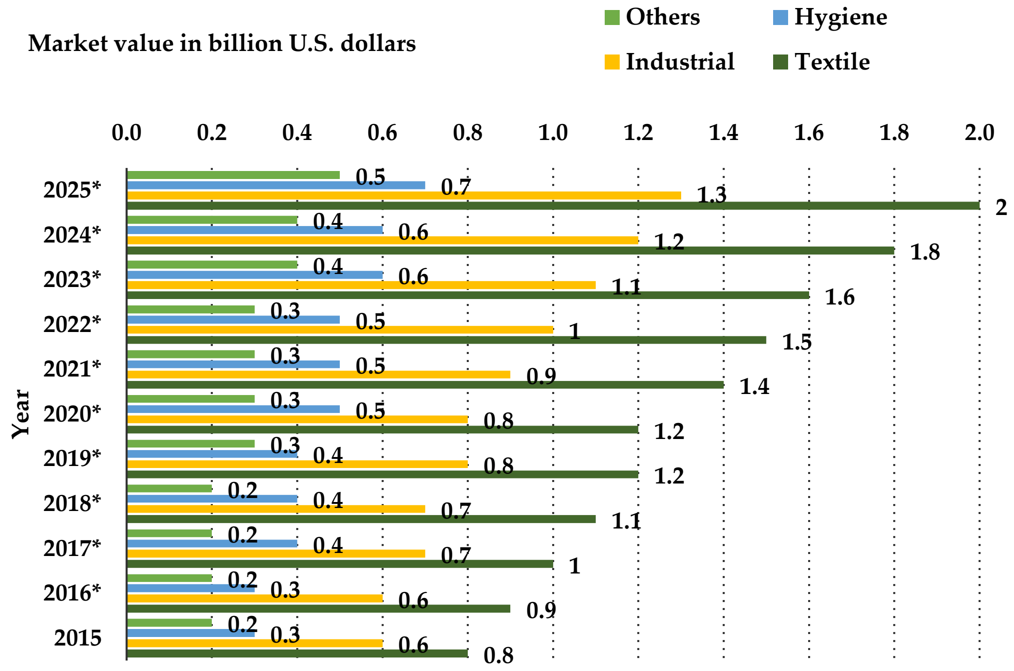

Figure 1. The Evolution of the market value of cellulose fiber in the United States across various applications from 2014 to 2025, expressed in billion U.S. dollars.

Methodology

The research roadmap for this study is illustrated in Figure 2. Initially, the cell-material simulation is meticulously modeled using MATLAB 2019b software as the first step. Subsequently, a dedicated model for the Circular Economy is expanded upon and integrated into the existing simulation. Finally, employing a heat map analysis, a comprehensive model is developed to conduct sensitivity analysis over time, enhancing our understanding of the dynamic aspects of the system.

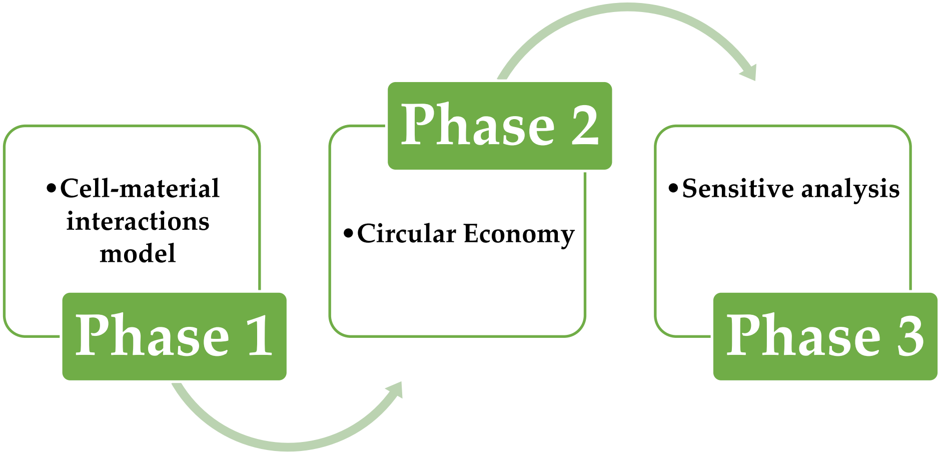

Figure 2. The research roadmap of present study.

Cell-material Simulation and modelling

The purpose of this study is to investigate the dynamic interplay between cell and material densities over time through a simulation-based approach. The mathematical model employed in this study represents the evolution of cell and material densities, considering key parameters governing cell proliferation, cell-material interaction, and material degradation. The simulation is based on a set of coupled ordinary differential equations (ODEs) describing the dynamics of cell (C) and material (M) densities over a specified time interval (t). The model is defined by the following differential Equations 1 and 2 [12-14].

$$dC/dt = k1 \cdot C - k2 \cdot C \cdot M \quad (1)$$

$$dM/dt = -k2 \cdot C \cdot M - k3 \cdot M \quad (2)$$

where:

C represents the cell density,

M represents the material density,

k_1 is the cell proliferation rate,

k_2 is the cell-material interaction rate, and

k_3 is the material degradation rate.

The system of ODEs is numerically solved using the MATLAB ode45 solver, providing a time-dependent evolution of cell and material densities. The simulation begins with initial conditions set at C(0)=1 and M(0)=1. The time vector (t) spans from 0 to 10 with a time step of 0.01, resulting in a total of N time points.

```
t=0:0.01:10
N=length(t)
```

The differential equations are integrated using the ode45 solver within a loop that iterates over each time point. At each iteration, the solver computes the solution over a small-time interval, and the results are used to update the cell and material densities for the next time step.

```
For i=2:N
Solve ODEs:[T,Y]=ode45(@(t,y)[dCdt(t,y(1),y(2));dMdt(t,y(1),y(2))],tspan,[C(i–1),M(i–1)])
Update densities: C(i)=Y(end,1), M(i)=Y(end,2)
```

The applied code for cell-material simulation is demonstrated in Code S.1.

Circular Economy Modelling and Sensitive Analysis

The simulation is governed by a set of coupled ODEs representing the circular economy system. The variables include cell density (C), material density (M), and recycled material density (R). The ODEs are defined as Equations 3-5 [15].

$$dC/dt = k_1 \cdot C - k_2 \cdot C \cdot M \tag{3}$$

$$dM/dt = -k_2 \cdot C \cdot M - k_3 \cdot M + k_4 \cdot R \tag{4}$$

$$dR/dt = k_3 \cdot M - k_4 \cdot R \tag{5}$$

where:

C is the cell density (cells/cm^3),

M is the material density (g/cm^3),

R is the recycled material density (g/cm^3),

k1 is the cell proliferation rate (1/s),

k2 is the cell-material interaction rate (1/(cell·g/cm^3·s)),

k3 is the material degradation rate (1/s), and

k4 is the recycling rate (1/s).

The simulation begins with initial conditions set at C(0)=1, M(0)=1, and R(0)=0. The time vector (t) spans from 0 to 10 seconds with a time step of 0.01, resulting in N time points. The simulation results are visualized through two subplots in the form of a butterfly diagram. Subplot 1 shows the evolution of cell density and recycled material density, while Subplot 2 presents a 3D butterfly diagram illustrating the relationships among cell density, material density, and recycled material density over time [16].

Results and discussions

In this section of research, a basic cell-material interactions model is developed with the application of MATLAB 2021-ChatGPT, which can be shown in Code S.1. The model includes two populations: cells and a material substrate. The initial conditions are set to 1 for both populations. The model parameters are set to three rates: cell proliferation rate, cell-material interaction rate, and material degradation rate. The differential equations describe the change in cell density and material density over time. The first equation describes the change in cell density as a function of the cell proliferation rate and the interaction between cells and the material substrate. The second equation describes the change in material density as a function of the interaction between cells and the material substrate and the material degradation rate. The differential equations are solved using the ode45 function, which solves ODEs numerically. The results are then plotted using the MATLAB plot function. The first subplot shows the change in cell density over time, while the second subplot shows the change in material density over time. In the present research, the outcomes of the simulation are demonstrated in Fig. 3. According to the figure, cell density changes during time and material density availability changes are demonstrated in Figs. 3-a and b, respectively.

From a biochemistry perspective, the cell proliferation rate and cell-material interaction rate are important parameters that determine cell behavior and tissue growth. The cell proliferation rate represents the rate of cell division, which is a crucial process for tissue regeneration and repair. The cell-material interaction rate represents the strength of the interaction between cells and the material substrate, which can influence cell adhesion, migration, and differentiation. These processes are important in the context of biomaterial design and tissue engineering, where materials are designed to interact with cells in specific ways to promote tissue regeneration or repair.

The material degradation rate is another important parameter that can affect the behavior of the system. In biochemistry, material degradation can occur due to enzymatic or non-enzymatic processes, and it can affect the mechanical properties and biocompatibility of materials. The rate of material degradation is therefore an important parameter to consider when designing materials for tissue engineering applications.

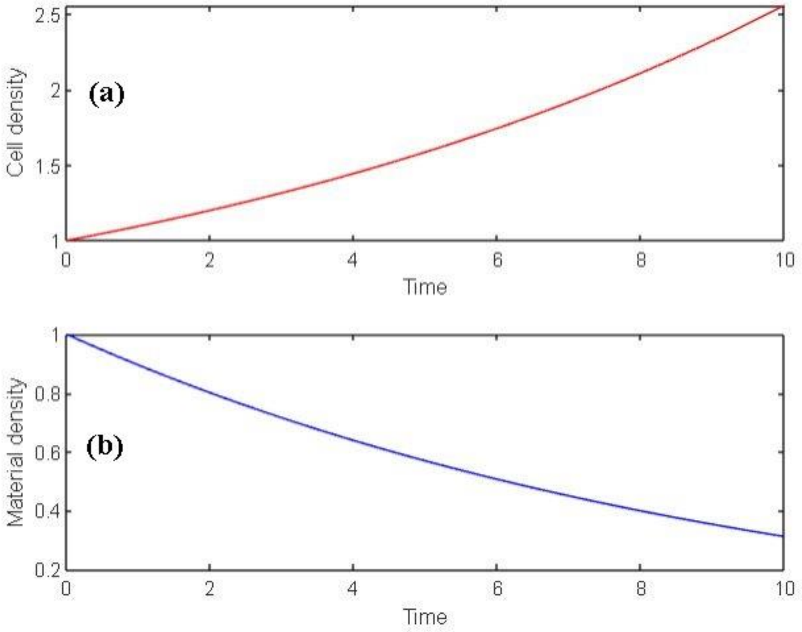

Figure 3. The simulation outputs of (a) cell and (b) material densities in cell-material interactions model.

The simulation results presented in Figs. 4a and 4b provide a comprehensive understanding of the dynamic interactions within a circular economy system. In the 2D butterfly diagram (Fig. 4a), the temporal evolution of cell density, material density, and recycled material density reveals intriguing patterns. The red curve representing cell density indicates an initial phase of active proliferation, coinciding with a gradual rise in the green curve representing recycled material density. This correlation suggests a positive relationship between cell proliferation and recycling processes. Material density, depicted by the blue curve, experiences fluctuations influenced by the intricate interplay between cell-material interactions and material degradation. The 3D butterfly diagram (Fig. 4b) offers a holistic view of the system's dynamics, showcasing the complex interactions and feedback loops among cell density, material density, and recycled material density. The trajectory in 3D space highlights the interdependence of these variables, emphasizing the need for a nuanced approach to circular economy modeling. The findings underscore the potential of recycling processes to maintain a balance between cell proliferation and material consumption, contributing to the sustainability of the system. Overall, these results provide valuable insights into optimizing recycling rates and material management strategies for a more sustainable and circular approach to resource utilization.

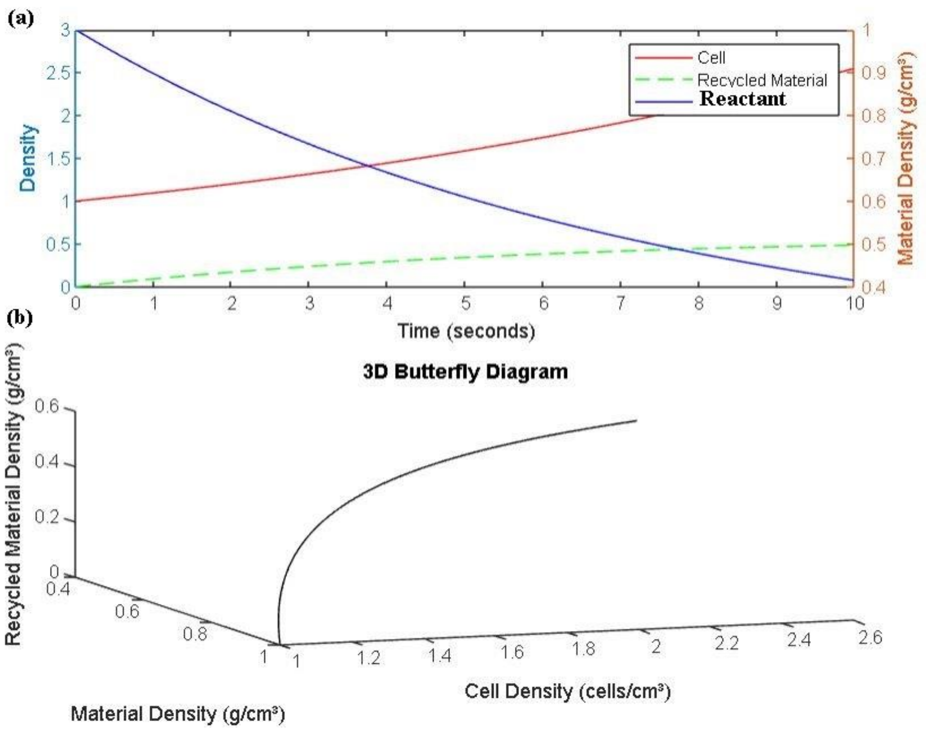

Figure 4. The outputs of (a) Temporal evolution of circular economy and (b) Holistic view of circular economy dynamics: 3D output.

The simulation of the circular economy system, as depicted in the heatmap, provides insights into the temporal evolution of cell density, material density, and recycled material density (Fig. 5). The heatmap visualizes the dynamic changes in these densities over the simulated time period, offering a concise overview of their interplay. The distinctive patterns in the heatmap underscore the complex interactions among cell proliferation, material consumption, and recycling processes. Notably, the gradual rise in cell density coincides with increased recycling, revealing a positive correlation between cell proliferation and recycling efforts. Material density exhibits fluctuations influenced by intricate cell-material interactions and material degradation. Overall, the heatmap serves as a concise representation, highlighting key dynamics in the circular economy model and providing a foundation for further analysis of sustainable resource management.

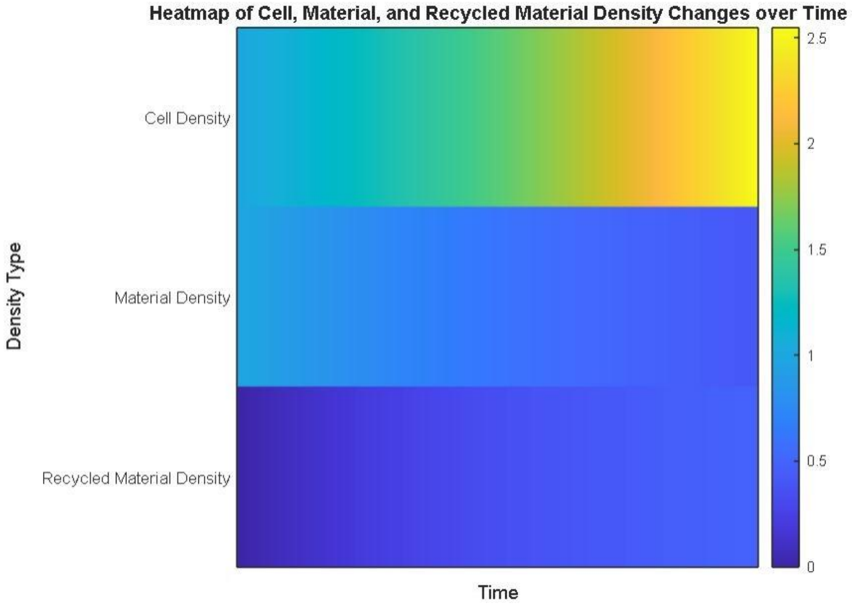

Figure 5. Circular economy dynamics unveiled: heatmap reveals temporal changes in cell, material, and recycled material densities, highlighting sustainability insights.

CONCLUSION

Recycled materials play a pivotal role in advancing sustainability within cellulose production. The reuse of materials in cellulose manufacturing processes not only conserves natural resources but also significantly reduces the ecological footprint associated with raw material extraction. Utilizing recycled materials contributes to lower energy consumption and diminishes the environmental burden of waste disposal. Moreover, it enhances the economic viability of cellulose production by minimizing production costs and promoting a closed-loop system. The incorporation of recycled materials underscores the cellulose industry's commitment to environmental stewardship, fostering a more sustainable and responsible approach to raw material utilization. In conclusion, the developed cell-material interactions model, implemented using MATLAB 2021-ChatGPT, provides a comprehensive understanding of dynamic processes crucial in biochemistry and circular economy systems. The simulation results reveal intricate patterns and interdependencies among cell density, material density, and recycled material density. From a biochemistry perspective, the cell proliferation rate and cell-material interaction rate emerge as pivotal factors influencing tissue growth and biomaterial design. Moreover, the material degradation rate underscores its significance in determining material properties for tissue engineering applications. In the context of a circular economy, the simulations highlight the positive correlation between cell proliferation and recycling efforts, emphasizing the potential of recycling processes to balance cell proliferation and material consumption. The findings underscore the need for a nuanced approach to circular economy modeling, offering valuable insights for optimizing recycling rates and material management strategies towards a sustainable and circular resource utilization paradigm.

CONFLICT OF INTERESTS

The authors confirm that there is no conflict of interests associated with this publication.

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Supplementary file

Code S.1

```
% Define the variables
t = 0:0.01:10; % Time vector
N = length(t); % Number of time points
C = zeros(N, 1); % Cell density
M = zeros(N, 1); % Material density
% Define the initial conditions
C(1) = 1;
M(1) = 1;
% Define the model parameters
k1 = 0.1; % Cell proliferation rate
k2 = 0.01; % Cell-material interaction rate
k3 = 0.1; % Material degradation rate
% Define the differential equations
dCdt = @(t, C, M) k1*C - k2*C.*M;
dMdt = @(t, C, M) -k2*C.*M - k3*M;

% Solve the differential equations
```

```
for i = 2:N
    tspan = [t(i-1), t(i)];
    [T, Y] = ode45(@(t, y) [dCdt(t, y(1), y(2)); dMdt(t, y(1), y(2))], tspan, [C(i-1), M(i-1)]);
    C(i) = Y(end, 1);
    M(i) = Y(end, 2);
end
% Plot the results
figure
subplot(2,1,1)
plot(t, C, 'r')
xlabel('Time')
ylabel('Cell density')
subplot(2,1,2)
plot(t, M, 'b')
xlabel('Time')
ylabel('Material density')
```

Code S.2

```
% Define the variables
t = 0:0.01:10; % Time vector (seconds)
N = length(t); % Number of time points
C = zeros(N, 1); % Cell density (cells/cm³)
M = zeros(N, 1); % Material density (g/cm³)
R = zeros(N, 1); % Recycled material density (g/cm³)
% Define the initial conditions
C(1) = 1; % Initial cell density (cells/cm³)
M(1) = 1; % Initial material density (g/cm³)
R(1) = 0; % Initial recycled material density (g/cm³)
% Define the model parameters
k1 = 0.1; % Cell proliferation rate (1/s)
k2 = 0.01; % Cell-material interaction rate (1/(cell·g/cm³·s))
k3 = 0.1; % Material degradation rate (1/s)
```

```
k4 = 0.05; % Recycling rate (1/s)
% Define the differential equations
dCdt = @(t, C, M, R) k1 * C - k2 * C .* M;
dMdt = @(t, C, M, R) -k2 * C .* M - k3 * M + k4 * R;
dRdt = @(t, C, M, R) k3 * M - k4 * R;
% Solve the differential equations
for i = 2:N
    tspan = [t(i-1), t(i)];
    [T, Y] = ode45(@(t, y) [dCdt(t, y(1), y(2), y(3)); dMdt(t, y(1), y(2), y(3)); dRdt(t, y(1), y(2), y(3))], tspan, [C(i-1), M(i-1), R(i-1)]);
    C(i) = Y(end, 1);
    M(i) = Y(end, 2);
    R(i) = Y(end, 3);
end
% Plot the results with a butterfly diagram
figure
subplot(2,1,1)
yyaxis left
plot(t, C, 'r', t, R, 'g')
xlabel('Time (seconds)')
ylabel('Density')
legend('Cell', 'Recycled Material')
yyaxis right
plot(t, M, 'b')
ylabel('Material Density (g/cm³)')
subplot(2,1,2)
plot3(C, M, R, 'k')
xlabel('Cell Density (cells/cm³)')
ylabel('Material Density (g/cm³)')
zlabel('Recycled Material Density (g/cm³)')
title('3D Butterfly Diagram')
```

Code S.3

```
% Define the variables

t = 0:0.01:10; % Time vector

N = length(t); % Number of time points

C = zeros(N, 1); % Cell density

M = zeros(N, 1); % Material density

R = zeros(N, 1); % Recycled material density

% Define the initial conditions

C(1) = 1;

M(1) = 1;

R(1) = 0;

% Define the model parameters

k1 = 0.1; % Cell proliferation rate

k2 = 0.01; % Cell-material interaction rate

k3 = 0.1; % Material degradation rate

k4 = 0.05; % Recycling rate

% Define the differential equations

dCdt = @(t, C, M, R) k1*C - k2*C.*M;

dMdt = @(t, C, M, R) -k2*C.*M - k3*M + k4*R;

dRdt = @(t, C, M, R) k3*M - k4*R;

% Solve the differential equations

for i = 2:N

    tspan = [t(i-1), t(i)];

    [T, Y] = ode45(@(t, y) [dCdt(t, y(1), y(2), y(3)); dMdt(t, y(1), y(2), y(3)); dRdt(t, y(1), y(2), y(3))],
tspan, [C(i-1), M(i-1), R(i-1)]);

    C(i) = Y(end, 1);

    M(i) = Y(end, 2);

    R(i) = Y(end, 3);

end

% Create a heatmap for Cell and Material Density changes over time

figure

h = heatmap(t, {'Cell Density', 'Material Density', 'Recycled Material Density'}, [C, M, R]');

xlabel('Time')
```

```
ylabel('Density Type')

title('Heatmap of Cell, Material, and Recycled Material Density Changes over Time')

% Increase grid size (optional)

h.GridVisible = 'off'; % Hide grid lines

h.Colormap = parula(256); % Change to a colormap with more colors
```