ภาคผนวก ก

ผลการศึกษาสัดส่วนผสมกากตะกอนส่วนเกินที่เหมาะสม

1. ค่า BOD 20 วัน ของกากตะกอนที่สัดส่วนผสมต่าง ๆ

ตารางที่ ก.1 ค่า BOD_{20} รายวัน ของสัดส่วนผสมกากตะกอน PS:SS ที่ 1:0

วันที่	ชั่วโมงที่ของวัน	$TBOD_{20}$ (mg/L)				$SBOD_{20}$ (mg/L)			
		ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD	ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD
1	4	141	141	141.00	0	113	84.4	98.7	20.22
	8	212	212	212.00	0	113	141.2	127.1	19.94
	12	282.5	353	317.75	49.85	169.4	169.4	169.4	0
	16	423.5	423.5	423.50	0	226	197.8	211.9	19.94
	20	423.5	494.5	459	50.2	226	226	226	0
	24	565	635	600	49.5	282	282	282	0
2	4	775	705	740	49.5	338	338	338	0
	8	920	775	847.5	102.53	368	424	396	39.6
	12	990	845	917.5	102.53	368	452	410	59.4
	16	1,130	920	1,025	148.49	424	536	480	79.2
	20	1,340	990	1,165	247.49	452	594	523	100.41
	24	1,485	1,060	1,272.5	300.52	480	650	565	120.21
3	4	1,625	1,270	1,447.5	251.02	536	678	607	100.41
	8	1,765	1,340	1,552.5	300.52	564	534	549	21.21
	12	1,905	1,410	1,657.5	350.02	594	820	707	159.81
	16	2,050	1,485	1,767.5	399.52	650	848	749	140.01
	20	2,190	1,555	1,872.5	449.01	734	876	805	100.41
	24	2,260	1,555	1,907.5	498.51	734	932	833	140.01
4	4	2,400	1,695	2,047.5	498.51	790	988	889	140.01
	8	2,470	1,765	2,117.5	498.51	820	1,074	947	179.61
	12	2,615	1,905	2,260.	502.05	876	1,158	1,017	199.4
	16	2,825	2,050	2,437.5	548.01	960	1,242	1,101	199.4
	20	2,895	2,050	2,472.5	597.51	988	1,328	1,158	240.42
	24	3,180	2,330	2,755	601.04	1,102	1,440	1,271	239
5	4	3,250	2,400	2,825	601.04	1,130	1,554	1,342	299.81
	8	3,460	2,540	3,000	650.54	1,214	1,638	1,426	299.81
	12	3,670	2,685	3,177.5	696.50	1,300	1,724	1,512	299.81
	16	3,670	2,755	3,212.5	647.00	1,328	1,808	1,568	339.41
	20	3,815	2,825	3,320	700.04	1,412	1,920	1,666	359.21

ตารางที่ ก.1 ค่า BOD_{20} รายวัน ของสัดส่วนผสมกากตะกอน PS:SS ที่ 1:0 (ต่อ)

วันที่	ชั่วโมงที่ของวัน	$TBOD_{20}$ (mg/L)				$SBOD_{20}$ (mg/L)			
		ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD	ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD
5 (ต่อ)	24	3,815	2,895	3,355	650.54	1,440	2,006	1,723	400.22
6	4	3,955	2,965	3,460	700.04	1,526	2,090	1,808	398.81
	8	4,025	3,105	3,565	650.54	1,610	2,204	1,907	420.02
	12	4,025	3,105	3,565	650.54	1,666	2,288	1,977	439.82
	16	3,955	3,035	3,495	650.54	1,694	2,344	2,019	459.62
	20	3,955	3,035	3,495	650.54	1,752	2,430	2,091	479.42
	24	4,025	3,180	3,602.5	597.51	1,808	2,514	2,161	499.22
7	4	4,095	3,180	3,637.5	647.00	1,864	2,570	2,217	499.22
	8	4,095	3,250	3,672.5	597.51	1,920	2,598	2,259	479.42
	12	4,165	3,250	3,707.5	647.00	1,978	2,656	2,317	479.42
	16	4,165	3,320	3,742.5	597.51	2,034	2,684	2,359	459.62
	20	4,165	3,390	3,777.5	548.01	2,090	2,684	2,387	420.02
	24	4,235	3,390	3,812.5	597.51	2,146	2,712	2,429	400.22
8	4	4,235	3,460	3,847.5	548.01	2,174	2,740	2,457	400.22
	8	4,235	3,460	3,847.5	548.01	2,232	2,768	2,500	379.01
	12	4,310	3,530	3,920	551.54	2,288	2,768	2,528	339.41
	16	4,310	3,530	3,920	551.54	2,344	2,796	2,570	319.61
	20	4,380	3,600	3,990	551.54	2,400	2,796	2,598	280.01
	24	4,310	3,600	3,955	502.05	2,458	2,796	2,627	239
9	4	4,380	3,670	4,025	502.05	2,486	2,824	2,655	239
	8	4,450	3,670	4,060	551.54	2,542	2,852	2,697	219.2
	12	4,450	3,745	4,097.5	498.51	2,598	2,852	2,725	179.61
	16	4,520	3,745	4,132.5	548.01	2,656	2,852	2,754	138.59
	20	4,520	3,815	4,167.5	498.51	2,656	2,882	2,769	159.81
	24	4,590	3,885	4,237.5	498.51	2,712	2,910	2,811	140.01
10	4	4,590	3,885	4,237.5	498.51	2,712	2,910	2,811	140.01
	8	4,660	3,885	4,272.5	548.01	2,740	2,938	2,839	140.01
	12	4,730	3,955	4,342.5	548.01	2,768	2,938	2,853	120.21
	16	4,730	3,955	4,342.5	548.01	2,768	2,966	2,867	140.01
	20	4,800	4,025	4,412.5	548.01	2,796	2,994	2,895	140.01
	24	4,800	4,025	4,412.5	548.01	2,796	2,994	2,895	140.01

ตารางที่ ก.1 ค่า BOD_{20} รายวัน ของสัดส่วนผสมกากตะกอน PS:SS ที่ 1:0 (ต่อ)

วันที่	ชั่วโมงที่ของวัน	$TBOD_{20}$ (mg/L)				$SBOD_{20}$ (mg/L)			
		ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD	ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD
11	4	4,800	4,095	4,447.5	498.51	2,824	3,022	2,923	140.01
	8	4,870	4,095	4,482.5	548.01	2,852	3,050	2,951	140.01
	12	4,870	4,165	4,517.5	498.51	2,882	3,050	2,966	118.79
	16	5,015	4,235	4,625	551.54	2,824	3,136	2,980	220.62
	20	5,085	4,380	4,732.5	498.51	2,938	3,164	3,051	159.81
	24	5,085	4,450	4,767.5	449.01	2,938	3,192	3,065	179.61
12	4	5,085	4,450	4,767.5	449.01	2,966	3,220	3,093	179.61
	8	5,085	4,520	4,802.5	399.52	2,966	3,220	3,093	179.61
	12	5,155	4,590	4,872.5	399.52	3,022	3,220	3,121	140.01
	16	5,225	4,590	4,907.5	449.01	3,022	3,248	3,135	159.81
	20	5,225	4,660	4,942.5	399.52	3,050	3,276	3,163	159.81
	24	5,155	4,660	4,907.5	350.02	3,050	3,304	3,177	179.61
13	4	5,225	4,730	4,977.5	350.02	3,078	3,276	3,177.	140.01
	8	5,225	4,730	4,977.5	350.02	3,108	3,304	3,206	138.59
	12	5,155	4,660	4,907.5	350.02	3,108	3,362	3,235	179.61
	16	5,085	4,590	4,837.5	350.02	3,108	3,276	3,192	118.79
	20	5,155	4,590	4,872.5	399.52	3,108	3,304	3,206	138.59
	24	5,155	4,660	4,907.5	350.02	3,136	3,334	3,235	140.01
14	4	5,155	4,660	4,907.5	350.02	3,164	3,334	3,249	120.21
	8	5,155	4,660	4,907.5	350.02	3,164	3,334	3,249	120.21
	12	5,155	4,660	4,907.5	350.02	3,164	3,362	3,263	140.01
	16	5,155	4,660	4,907.5	350.02	3,192	3,362	3,277	120.21
	20	5,225	4,730	4,977.5	350.02	3,192	3,390	3,291	140.01
	24	5,225	4,730	4,977.5	350.02	3,220	3,390	3,305	120.21
15	4	5,225	4,730	4,977.5	350.02	3,220	3,390	3,305	120.21
	8	5,085	4,590	4,837.5	350.02	3,192	3,390	3,291	140.01
	12	5,225	4,730	4,977.5	350.02	3,248	3,418	3,333	120.21
	16	5,225	4,730	4,977.5	350.02	3,248	3,418	3,333	120.21
	20	5,225	4,800	5,012.5	300.52	3,276	3,446	3,361	120.21
	24	5,225	4,800	5,012.5	300.52	3,276	3,446	3,361	120.21

ตารางที่ ก.1 ค่า BOD_{20} รายวัน ของสัดส่วนผสมกากตะกอน PS:SS ที่ 1:0 (ต่อ)

วันที่	ชั่วโมงที่ของวัน	$TBOD_{20}$ (mg/L)				$SBOD_{20}$ (mg/L)			
		ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD	ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD
16	4	5,225	4,800	5,012.5	300.52	3,304	3,474	3,389	120.21
	8	5,225	4,800	5,012.5	300.52	3,304	3,474	3,389	120.21
	12	5,295	4,800	5,047.5	350.02	3,334	3,474	3,404	98.99
	16	5,295	4,800	5,047.5	350.02	3,334	3,502	3,418	118.79
	20	5,225	4,800	5,012.5	300.52	3,334	3,502	3,418	118.79
	24	5,295	4,870	5,082.5	300.52	3,362	3,530	3,446	118.79
17	4	5,295	4,870	5,082.5	300.52	3,362	3,530	3,446	118.79
	8	5,225	4,870	5,047.5	251.02	3,362	3,560	3,461	140.01
	12	5,295	4,870	5,082.5	300.52	3,362	3,560	3,461	140.01
	16	5,295	4,870	5,082.5	300.52	3,390	3,588	3,489	140.01
	20	5,295	4,870	5,082.5	300.52	3,390	3,588	3,489	140.01
	24	5,295	4,945	5,120	247.49	3,390	3,588	3,489	140.01
18	4	5,295	4,945	5,120	247.49	3,418	3,616	3,517	140.01
	8	5,295	4,870	5,082.5	300.52	3,390	3,616	3,503	159.81
	12	5,295	4,945	5,120	247.49	3,418	3,616	3,517	140.01
	16	5,295	4,945	5,120	247.49	3,446	3,644	3,545	140.01
	20	5,295	4,945	5,120	247.49	3,446	3,644	3,545	140.01
	24	5,295	4,945	5,120	247.49	3,418	3,672	3,545	179.61
19	4	5,295	5,015	5,155	197.99	3,446	3,672	3,559	159.81
	8	5,295	4,945	5,120	247.49	3,446	3,672	3,559	159.81
	12	5,365	5,015	5,190	247.49	3,446	3,672	3,559	159.81
	16	5,295	4,945	5,120	247.49	3,446	3,672	3,559	159.81
	20	5,365	4,945	5,155	296.98	3,474	3,700	3,587	159.81
	24	5,365	5,015	5,190	247.49	3,474	3,700	3,587	159.81
20	4	5,365	5,015	5,190	247.49	3,502	3,700	3,601	140.01
	8	5,365	5,015	5,190	247.49	3,502	3,700	3,601	140.01
	12	5,365	5,085	5,225	197.99	3,502	3,728	3,615	159.81
	16	5,365	5,085	5,225	197.99	3,502	3,728	3,615	159.81
	20	5,365	5,085	5,225	197.99	3,502	3,728	3,615	159.81
	24	5,365	5,015	5,190	247.49	3,502	3,756	3,629	179.61

ตารางที่ ก.2 ค่า BOD_{20} รายวัน ของสัดส่วนผสมกากตะกอน PS:SS ที่ 3:1

วันที่	ชั่วโมงที่ของวัน	$TBOD_{20}$ (mg/L)				$SBOD_{20}$ (mg/L)			
		ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD	ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD
1	4	80	80	80	0	undef	undef	undef	0
	8	160	160	160	0	153	153	153	0
	12	160	160	160	0	153	153	153	0
	16	321	321	321	0	153	153	153	0
	20	321	321	321	0	307	307	307	0
	24	480	480	480	0	126	126	126	0
2	4	undef	undef	undef	0	461	461	461	0
	8	562	562	562	0	307	307	307	0
	12	642	642	642	0	461	461	461	0
	16	721	721	721	0	461	461	461	0
	20	721	721	721	0	461	461	461	0
	24	880	880	880	0	461	461	461	0
3	4	880	880	880	0	461	461	461	0
	8	1,042	1,042	1,042	0	767	767	767	0
	12	1,042	1,042	1,042	0	767	767	767	0
	16	1,122	1,122	1,122	0	767	767	767	0
	20	1,201	1,201	1,201	0	767	767	767	0
	24	1,201	1,201	1,201	0	919	919	919	0
4	4	1,363	1,363	1,363	0	919	919	919	0
	8	1,443	1,443	1,443	0	1,077	1,077	1,077	0
	12	1,605	1,605	1,605	0	919	919	919	0
	16	1,764	1,764	1,764	0	1,077	1,077	1,077	0
	20	1,843	1,843	1,843	0	undef	undef	undef	0
	24	1,923	1,923	1,923	0	1,077	1,077	1,077	0
5	4	2,085	2,085	2,085	0	1,077	1,077	1,077	0
	8	2,085	2,085	2,085	0	1,077	1,077	1,077	0
	12	2,244	2,244	2,244	0	1,229	1,229	1,229	0
	16	2,244	2,244	2,244	0	1,382	1,382	1,382	0
	20	2,326	2,326	2,326	0	1,382	1,382	1,382	0
	24	963	963	963	0	1,534	1,534	1,534	0
6	4	2,405	2,405	2,405	0	1,229	1,229	1,229	0

ตารางที่ ก.2 ค่า BOD_{20} รายวัน ของสัดส่วนผสมกากตะกอน PS:SS ที่ 3:1 (ต่อ)

วันที่	ชั่วโมงที่ของวัน	$TBOD_{20}$ (mg/L)				$SBOD_{20}$ (mg/L)			
		ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD	ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD
6 (ต่อ)	8	2,405	2,405	2,405	0	1,534	1,534	1,534	0
	12	2,485	2,485	2,485	0	1,382	1,382	1,382	0
	16	2,485	2,485	2,485	0	1,382	1,382	1,382	0
	20	2,565	2,565	2,565	0	1,686	1,686	1,686	0
	24	2,565	2,565	2,565	0	1,534	1,534	1,534	0
7	4	2,644	2,644	2,644	0	1,534	1,534	1,534	0
	8	2,644	2,644	2,644	0	1,534	1,534	1,534	0
	12	2,644	2,644	2,644	0	1,686	1,686	1,686	0
	16	2,726	2,726	2,726	0	1,686	1,686	1,686	0
	20	2,644	2,644	2,644	0	1,534	1,534	1,534	0
	24	2,806	2,806	2,806	0	1,844	1,844	1,844	0
8	4	2,806	2,806	2,806	0	1,686	1,686	1,686	0
	8	2,726	2,726	2,726	0	1,534	1,534	1,534	0
	12	2,806	2,806	2,806	0	1,686	1,686	1,686	0
	16	2,885	2,885	2,885	0	1,686	1,686	1,686	0
	20	2,885	2,885	2,885	0	1,534	1,534	1,534	0
	24	2,885	2,885	2,885	0	1,996	1,996	1,996	0
9	4	2,885	2,885	2,885	0	1,686	1,686	1,686	0
	8	2,885	2,885	2,885	0	1,844	1,844	1,844	0
	12	2,885	2,885	2,885	0	1,686	1,686	1,686	0
	16	2,885	2,885	2,885	0	1,686	1,686	1,686	0
	20	2,965	2,965	2,965	0	1,844	1,844	1,844	0
	24	2,965	2,965	2,965	0	1,844	1,844	1,844	0
10	4	2,965	2,965	2,965	0	1,844	1,844	1,844	0
	8	2,965	2,965	2,965	0	1,686	1,686	1,686	0
	12	3,047	3,047	3,047	0	1,996	1,996	1,996	0
	16	2,965	2,965	2,965	0	1,844	1,844	1,844	0
	20	3,047	3,047	3,047	0	1,844	1,844	1,844	0
	24	3,047	3,047	3,047	0	1,844	1,844	1,844	0
11	4	3,047	3,047	3,047	0	1,844	1,844	1,844	0
	8	3,127	3,127	3,127	0	1,844	1,844	1,844	0

ตารางที่ ก.2 ค่า BOD_{20} รายวัน ของสัดส่วนผสมกากตะกอน PS:SS ที่ 3:1 (ต่อ)

วันที่	ชั่วโมงที่ของวัน	$TBOD_{20}$ (mg/L)				$SBOD_{20}$ (mg/L)			
		ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD	ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD
11 (ต่อ)	12	3,127	3,127	3,127	0	1,996	1,996	1,996	0
	16	3,127	3,127	3,127	0	1,996	1,996	1,996	0
	20	3,127	3,127	3,127	0	1,996	1,996	1,996	0
	24	3,127	3,127	3,127	0	1,996	1,996	1,996	0
12	4	3,206	3,206	3,206	0	1,844	1,844	1,844	0
	8	3,206	3,206	3,206	0	1,844	1,844	1,844	0
	12	3,206	3,206	3,206	0	2,149	2,149	2,149	0
	16	3,206	3,206	3,206	0	1,844	1,844	1,844	0
	20	3,206	3,206	3,206	0	2,149	2,149	2,149	0
	24	3,286	3,286	3,286	0	2,301	2,301	2,301	0
13	4	3,286	3,286	3,286	0	2,149	2,149	2,149	0
	8	3,286	3,286	3,286	0	2,301	2,301	2,301	0
	12	3,286	3,286	3,286	0	2,149	2,149	2,149	0
	16	3,368	3,368	3,368	0	1,996	1,996	1,996	0
	20	3,368	3,368	3,368	0	2,301	2,301	2,301	0
	24	3,448	3,448	3,448	0	2,301	2,301	2,301	0
14	4	3,448	3,448	3,448	0	2,301	2,301	2,301	0
	8	3,527	3,527	3,527	0	2,149	2,149	2,149	0
	12	3,527	3,527	3,527	0	2,149	2,149	2,149	0
	16	3,527	3,527	3,527	0	2,149	2,149	2,149	0
	20	3,527	3,527	3,527	0	2,149	2,149	2,149	0
	24	3,607	3,607	3,607	0	2,301	2,301	2,301	0
15	4	3,607	3,607	3,607	0	2,301	2,301	2,301	0
	8	3,607	3,607	3,607	0	2,149	2,149	2,149	0
	12	3,607	3,607	3,607	0	2,301	2,301	2,301	0
	16	3,607	3,607	3,607	0	2,149	2,149	2,149	0
	20	3,686	3,686	3,686	0	2,459	2,459	2,459	0
	24	3,686	3,686	3,686	0	2,459	2,459	2,459	0
16	4	3,686	3,686	3,686	0	2,301	2,301	2,301	0
	8	3,769	3,769	3,769	0	2,149	2,149	2,149	0
	12	3,769	3,769	3,769	0	2,301	2,301	2,301	0

ตารางที่ ก.2 ค่า BOD_{20} รายวัน ของสัดส่วนผสมกากตะกอน PS:SS ที่ 3:1 (ต่อ)

วันที่	ชั่วโมงที่ของวัน	$TBOD_{20}$ (mg/L)				$SBOD_{20}$ (mg/L)			
		ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD	ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD
16 (ต่อ)	16	3,769	3,769	3,769	0	2,611	2,611	2,611	0
	20	3,848	3,848	3,848	0	2,301	2,301	2,301	0
	24	3,848	3,848	3,848	0	2,611	2,611	2,611	0
17	4	3,848	3,848	3,848	0	2,611	2,611	2,611	0
	8	3,848	3,848	3,848	0	2,301	2,301	2,301	0
	12	3,848	3,848	3,848	0	2,459	2,459	2,459	0
	16	3,928	3,928	3,928	0	2,301	2,301	2,301	0
	20	3,928	3,928	3,928	0	2,611	2,611	2,611	0
	24	3,928	3,928	3,928	0	2,459	2,459	2,459	0
18	4	4,007	4,007	4,007	0	2,764	2,764	2,764	0
	8	4,007	4,007	4,007	0	2,611	2,611	2,611	0
	12	4,007	4,007	4,007	0	2,301	2,301	2,301	0
	16	4,007	4,007	4,007	0	2,459	2,459	2,459	0
	20	4,007	4,007	4,007	0	2,459	2,459	2,459	0
	24	4,090	4,090	4,090	0	2,764	2,764	2,764	0
19	4	4,007	4,007	4,007	0	2,459	2,459	2,459	0
	8	4,090	4,090	4,090	0	2,611	2,611	2,611	0
	12	4,090	4,090	4,090	0	2,611	2,611	2,611	0
	16	4,090	4,090	4,090	0	2,611	2,611	2,611	0
	20	4,090	4,090	4,090	0	2,764	2,764	2,764	0
	24	4,090	4,090	4,090	0	2,764	2,764	2,764	0
20	4	4,169	4,169	4,169	0	2,764	2,764	2,764	0
	8	4,090	4,090	4,090	0	2,764	2,764	2,764	0
	12	4,169	4,169	4,169	0	2,764	2,764	2,764	0
	16	4,169	4,169	4,169	0	2,611	2,611	2,611	0
	20	4,169	4,169	4,169	0	2,764	2,764	2,764	0
	24	4,249	4,249	4,249	0	2,764	2,764	2,764	0

ตารางที่ ก.3 ค่า BOD_{20} รายวัน ของสัดส่วนผสมกากตะกอน PS:SS ที่ 1:1

วันที่	ชั่วโมงที่ของวัน	$TBOD_{20}$ (mg/L)				$SBOD_{20}$ (mg/L)			
		ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD	ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD
1	4	142	142	142	0	-	-	-	0
	8	285	285	285	0	105	105	105	0
	12	285	285	285	0	105	105	105	0
	16	355	355	355	0	105	105	105	0
	20	499	499	499	0	210	210	210	0
	24	570	570	570	0	210	210	210	0
2	4	undef	undef	undef	0	315	315	315	0
	8	781	781	781	0	210	210	210	0
	12	925	925	925	0	315	315	315	0
	16	995	995	995	0	315	315	315	0
	20	995	995	995	0	173	173	173	0
	24	1,066	1,066	1,066	0	420	420	420	0
3	4	1,139	1,139	1,139	0	315	315	315	0
	8	1,210	1,210	1,210	0	420	420	420	0
	12	1,280	1,280	1,280	0	525	525	525	0
	16	1,351	1,351	1,351	0	420	420	420	0
	20	1,351	1,351	1,351	0	420	420	420	0
	24	1,424	1,424	1,424	0	630	630	630	0
4	4	1,424	1,424	1,424	0	525	525	525	0
	8	1,494	1,494	1,494	0	630	630	630	0
	12	1,565	1,565	1,565	0	525	525	525	0
	16	1,565	1,565	1,565	0	630	630	630	0
	20	1,635	1,635	1,635	0	-	-	-	0
	24	1,635	1,635	1,635	0	630	630	630	0
5	4	1,706	1,706	1,706	0	630	630	630	0
	8	1,706	1,706	1,706	0	630	630	630	0
	12	1,706	1,706	1,706	0	736	736	736	0
	16	1,706	1,706	1,706	0	841	841	841	0
	20	1,850	1,850	1,850	0	841	841	841	0
	24	570	570	570	0	841	841	841	0

ตารางที่ ก.3 ค่า BOD_{20} รายวัน ของสัดส่วนผสมกากตะกอน PS:SS ที่ 1:1 (ต่อ)

วันที่	ชั่วโมงที่ของวัน	$TBOD_{20}$ (mg/L)				$SBOD_{20}$ (mg/L)			
		ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD	ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD
6	4	1,850	1,850	1,850	0	736	736	736	0
	8	1,850	1,850	1,850	0	841	841	841	0
	12	1,920	1,920	1,920	0	841	841	841	0
	16	1,920	1,920	1,920	0	841	841	841	0
	20	1,991	1,991	1,991	0	945	945	945	0
	24	1,991	1,991	1,991	0	945	945	945	0
7	4	1,991	1,991	1,991	0	945	945	945	0
	8	2,064	2,064	2,064	0	945	945	945	0
	12	2,064	2,064	2,064	0	1,049	1,049	1,049	0
	16	2,064	2,064	2,064	0	1,049	1,049	1,049	0
	20	2,064	2,064	2,064	0	1,049	1,049	1,049	0
	24	2,134	2,134	2,134	0	1,153	1,153	1,153	0
8	4	2,134	2,134	2,134	0	1,153	1,153	1,153	0
	8	2,134	2,134	2,134	0	1,049	1,049	1,049	0
	12	2,134	2,134	2,134	0	1,153	1,153	1,153	0
	16	2,276	2,276	2,276	0	1,153	1,153	1,153	0
	20	2,276	2,276	2,276	0	1,049	1,049	1,049	0
	24	2,276	2,276	2,276	0	1,257	1,257	1,257	0
9	4	2,276	2,276	2,276	0	1,049	1,049	1,049	0
	8	2,346	2,346	2,346	0	1,153	1,153	1,153	0
	12	2,276	2,276	2,276	0	1,153	1,153	1,153	0
	16	2,346	2,346	2,346	0	1,153	1,153	1,153	0
	20	2,419	2,419	2,419	0	1,257	1,257	1,257	0
	24	2,419	2,419	2,419	0	1,257	1,257	1,257	0
10	4	2,419	2,419	2,419	0	1,257	1,257	1,257	0
	8	2,419	2,419	2,419	0	1,153	1,153	1,153	0
	12	2,490	2,490	2,490	0	1,257	1,257	1,257	0
	16	2,490	2,490	2,490	0	1,257	1,257	1,257	0
	20	2,490	2,490	2,490	0	1,257	1,257	1,257	0
	24	2,490	2,490	2,490	0	1,257	1,257	1,257	0

ตารางที่ ก.3 ค่า BOD_{20} รายวัน ของสัดส่วนผสมกากตะกอน PS:SS ที่ 1:1 (ต่อ)

วันที่	ชั่วโมงที่ของวัน	$TBOD_{20}$ (mg/L)				$SBOD_{20}$ (mg/L)			
		ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD	ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD
11	4	2,490	2,490	2,490	0	1,257	1,257	1,257	0
	8	2,490	2,490	2,490	0	1,257	1,257	1,257	0
	12	2,490	2,490	2,490	0	1,369	1,369	1,369	0
	16	2,560	2,560	2,560	0	1,369	1,369	1,369	0
	20	2,490	2,490	2,490	0	1,369	1,369	1,369	0
	24	2,560	2,560	2,560	0	1,369	1,369	1,369	0
12	4	2,560	2,560	2,560	0	1,257	1,257	1,257	0
	8	2,560	2,560	2,560	0	1,257	1,257	1,257	0
	12	2,560	2,560	2,560	0	1,369	1,369	1,369	0
	16	2,631	2,631	2,631	0	1,257	1,257	1,257	0
	20	2,560	2,560	2,560	0	1,473	1,473	1,473	0
	24	2,631	2,631	2,631	0	1,473	1,473	1,473	0
13	4	2,631	2,631	2,631	0	1,577	1,577	1,577	0
	8	2,704	2,704	2,704	0	1,473	1,473	1,473	0
	12	2,631	2,631	2,631	0	1,369	1,369	1,369	0
	16	2,704	2,704	2,704	0	1,577	1,577	1,577	0
	20	2,704	2,704	2,704	0	1,577	1,577	1,577	0
	24	2,704	2,704	2,704	0	1,577	1,577	1,577	0
14	4	2,775	2,775	2,775	0	1,473	1,473	1,473	0
	8	2,775	2,775	2,775	0	1,473	1,473	1,473	0
	12	2,845	2,845	2,845	0	1,473	1,473	1,473	0
	16	2,845	2,845	2,845	0	1,577	1,577	1,577	0
	20	2,845	2,845	2,845	0	1,681	1,681	1,681	0
	24	2,845	2,845	2,845	0	1,577	1,577	1,577	0
15	4	2,845	2,845	2,845	0	1,577	1,577	1,577	0
	8	2,845	2,845	2,845	0	1,577	1,577	1,577	0
	12	2,845	2,845	2,845	0	1,577	1,577	1,577	0
	16	2,845	2,845	2,845	0	1,577	1,577	1,577	0
	20	2,916	2,916	2,916	0	1,681	1,681	1,681	0
	24	2,845	2,845	2,845	0	1,681	1,681	1,681	0

ตารางที่ ก.3 ค่า BOD_{20} รายวัน ของสัดส่วนผสมกากตะกอน PS:SS ที่ 1:1 (ต่อ)

วันที่	ชั่วโมงที่ของวัน	$TBOD_{20}$ (mg/L)				$SBOD_{20}$ (mg/L)			
		ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD	ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD
16	4	2,916	2,916	2,916	0	1,577	1,577	1,577	0
	8	2,989	2,989	2,989	0	1,681	1,681	1,681	0
	12	2,916	2,916	2,916	0	1,681	1,681	1,681	0
	16	2,916	2,916	2,916	0	1,681	1,681	1,681	0
	20	2,989	2,989	2,989	0	1,786	1,786	1,786	0
	24	2,989	2,989	2,989	0	1,786	1,786	1,786	0
17	4	3,059	3,059	3,059	0	1,681	1,681	1,681	0
	8	2,989	2,989	2,989	0	1,681	1,681	1,681	0
	12	2,989	2,989	2,989	0	1,577	1,577	1,577	0
	16	3,059	3,059	3,059	0	1,786	1,786	1,786	0
	20	3,059	3,059	3,059	0	1,681	1,681	1,681	0
	24	2,989	2,989	2,989	0	1,786	1,786	1,786	0
18	4	3,059	3,059	3,059	0	1,786	1,786	1,786	0
	8	3,130	3,130	3,130	0	1,681	1,681	1,681	0
	12	3,059	3,059	3,059	0	1,681	1,681	1,681	0
	16	3,059	3,059	3,059	0	1,786	1,786	1,786	0
	20	3,059	3,059	3,059	0	1,786	1,786	1,786	0
	24	3,130	3,130	3,130	0	1,681	1,681	1,681	0
19	4	3,130	3,130	3,130	0	1,786	1,786	1,786	0
	8	3,130	3,130	3,130	0	1,786	1,786	1,786	0
	12	3,130	3,130	3,130	0	1,786	1,786	1,786	0
	16	3,130	3,130	3,130	0	1,890	1,890	1,890	0
	20	3,200	3,200	3,200	0	1,786	1,786	1,786	0
	24	3,130	3,130	3,130	0	1,890	1,890	1,890	0
20	4	3,200	3,200	3,200	0	1,786	1,786	1,786	0
	8	3,200	3,200	3,200	0	1,786	1,786	1,786	0
	12	3,271	3,271	3,271	0	1,786	1,786	1,786	0
	16	3,271	3,271	3,271	0	1,786	1,786	1,786	0
	20	3,271	3,271	3,271	0	1,786	1,786	1,786	0
	24	3,344	3,344	3,344	0	1,786	1,786	1,786	0

ตารางที่ ก.4 ค่า BOD_{20} รายวัน ของสัดส่วนผสมกากตะกอน PS:SS ที่ 1:3

วันที่	ชั่วโมงที่ของวัน	$TBOD_{20}$ (mg/L)				$SBOD_{20}$ (mg/L)			
		ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD	ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD
1	4	104	104	104	0	48	48	48	0
	8	209	209	209	0	145	145	145	0
	12	209	209	209	0	145	145	145	0
	16	313	313	313	0	97	97	97	0
	20	209	209	209	0	194	194	194	0
	24	313	313	313	0	242	242	242	0
2	4	undef	undef	undef	0	undef	undef	undef	0
	8	313	313	313	0	194	194	194	0
	12	418	418	418	0	194	194	194	0
	16	418	418	418	0	242	242	242	0
	20	418	418	418	0	242	242	242	0
	24	522	522	522	0	242	242	242	0
3	4	522	522	522	0	291	291	291	0
	8	625	625	625	0	242	242	242	0
	12	625	625	625	0	242	242	242	0
	16	625	625	625	0	291	291	291	0
	20	625	625	625	0	291	291	291	0
	24	625	625	625	0	339	339	339	0
4	4	733	733	733	0	339	339	339	0
	8	733	733	733	0	388	388	388	0
	12	733	733	733	0	339	339	339	0
	16	733	733	733	0	339	339	339	0
	20	733	733	733	0	339	339	339	0
	24	733	733	733	0	388	388	388	0
5	4	836	836	836	0	388	388	388	0
	8	733	733	733	0	436	436	436	0
	12	836	836	836	0	388	388	388	0
	16	836	836	836	0	436	436	436	0
	20	940	940	940	0	436	436	436	0
	24	undef	undef	undef	0	undef	undef	undef	0

ตารางที่ ก.4 ค่า BOD_{20} รายวัน ของสัดส่วนผสมกากตะกอน PS:SS ที่ 1:3 (ต่อ)

วันที่	ชั่วโมงที่ของวัน	$TBOD_{20}$ (mg/L)				$SBOD_{20}$ (mg/L)			
		ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD	ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD
6	4	940	940	940	0	436	436	436	0
	8	940	940	940	0	484	484	484	0
	12	940	940	940	0	484	484	484	0
	16	940	940	940	0	436	436	436	0
	20	1,043	1,043	1,043	0	484	484	484	0
	24	1,043	1,043	1,043	0	484	484	484	0
7	4	1,043	1,043	1,043	0	532	532	532	0
	8	1,043	1,043	1,043	0	580	580	580	0
	12	1,043	1,043	1,043	0	484	484	484	0
	16	1,043	1,043	1,043	0	532	532	532	0
	20	1,043	1,043	1,043	0	532	532	532	0
	24	1,147	1,147	1,147	0	532	532	532	0
8	4	1,147	1,147	1,147	0	532	532	532	0
	8	1,043	1,043	1,043	0	580	580	580	0
	12	1,147	1,147	1,147	0	580	580	580	0
	16	1,147	1,147	1,147	0	580	580	580	0
	20	1,147	1,147	1,147	0	580	580	580	0
	24	1,147	1,147	1,147	0	580	580	580	0
9	4	1,254	1,254	1,254	0	631	631	631	0
	8	1,254	1,254	1,254	0	580	580	580	0
	12	1,147	1,147	1,147	0	631	631	631	0
	16	1,254	1,254	1,254	0	580	580	580	0
	20	1,254	1,254	1,254	0	631	631	631	0
	24	1,254	1,254	1,254	0	679	679	679	0
10	4	1,358	1,358	1,358	0	679	679	679	0
	8	1,358	1,358	1,358	0	679	679	679	0
	12	1,358	1,358	1,358	0	631	631	631	0
	16	1,358	1,358	1,358	0	679	679	679	0
	20	1,358	1,358	1,358	0	679	679	679	0
	24	1,358	1,358	1,358	0	679	679	679	0

ตารางที่ ก.4 ค่า BOD_{20} รายวัน ของสัดส่วนผสมกากตะกอน PS:SS ที่ 1:3 (ต่อ)

วันที่	ชั่วโมงที่	$TBOD_{20}$ (mg/L)				$SBOD_{20}$ (mg/L)			
	ของวัน	ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD	ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD
11	4	1,358	1,358	1,358	0	679	679	679	0
	8	1,358	1,358	1,358	0	727	727	727	0
	12	1,358	1,358	1,358	0	727	727	727	0
	16	1,462	1,462	1,462	0	727	727	727	0
	20	1,462	1,462	1,462	0	727	727	727	0
	24	1,462	1,462	1,462	0	775	775	775	0
12	4	1,462	1,462	1,462	0	727	727	727	0
	8	1,462	1,462	1,462	0	727	727	727	0
	12	1,462	1,462	1,462	0	727	727	727	0
	16	1,565	1,565	1,565	0	727	727	727	0
	20	1,565	1,565	1,565	0	727	727	727	0
	24	1,565	1,565	1,565	0	727	727	727	0
13	4	1,672	1,672	1,672	0	727	727	727	0
	8	1,672	1,672	1,672	0	775	775	775	0
	12	1,672	1,672	1,672	0	775	775	775	0
	16	1,776	1,776	1,776	0	775	775	775	0
	20	1,776	1,776	1,776	0	775	775	775	0
	24	1,776	1,776	1,776	0	775	775	775	0
14	4	1,776	1,776	1,776	0	775	775	775	0
	8	1,880	1,880	1,880	0	775	775	775	0
	12	1,880	1,880	1,880	0	775	775	775	0
	16	1,983	1,983	1,983	0	823	823	823	0
	20	1,880	1,880	1,880	0	823	823	823	0
	24	1,983	1,983	1,983	0	823	823	823	0
15	4	1,983	1,983	1,983	0	823	823	823	0
	8	1,983	1,983	1,983	0	823	823	823	0
	12	1,983	1,983	1,983	0	871	871	871	0
	16	1,983	1,983	1,983	0	871	871	871	0
	20	1,983	1,983	1,983	0	871	871	871	0
	24	1,983	1,983	1,983	0	871	871	871	0

ตารางที่ ก.4 ค่า BOD_{20} รายวัน ของสัดส่วนผสมกากตะกอน PS:SS ที่ 1:3 (ต่อ)

วันที่	ชั่วโมงที่ของวัน	$TBOD_{20}$ (mg/L)				$SBOD_{20}$ (mg/L)			
		ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD	ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD
16	4	1,983	1,983	1,983	0	823	823	823	0
	8	1,983	1,983	1,983	0	871	871	871	0
	12	2,091	2,091	2,091	0	919	919	919	0
	16	2,091	2,091	2,091	0	823	823	823	0
	20	2,091	2,091	2,091	0	871	871	871	0
	24	2,091	2,091	2,091	0	871	871	871	0
17	4	2,091	2,091	2,091	0	919	919	919	0
	8	2,091	2,091	2,091	0	871	871	871	0
	12	2,091	2,091	2,091	0	919	919	919	0
	16	2,091	2,091	2,091	0	919	919	919	0
	20	2,091	2,091	2,091	0	871	871	871	0
	24	2,091	2,091	2,091	0	919	919	919	0
18	4	2,194	2,194	2,194	0	919	919	919	0
	8	2,194	2,194	2,194	0	967	967	967	0
	12	2,091	2,091	2,091	0	967	967	967	0
	16	2,194	2,194	2,194	0	967	967	967	0
	20	2,194	2,194	2,194	0	967	967	967	0
	24	2,298	2,298	2,298	0	919	919	919	0
19	4	2,194	2,194	2,194	0	967	967	967	0
	8	2,298	2,298	2,298	0	967	967	967	0
	12	2,298	2,298	2,298	0	967	967	967	0
	16	2,194	2,194	2,194	0	967	967	967	0
	20	2,194	2,194	2,194	0	967	967	967	0
	24	2,298	2,298	2,298	0	967	967	967	0
20	4	2,298	2,298	2,298	0	967	967	967	0
	8	2,298	2,298	2,298	0	967	967	967	0
	12	2,298	2,298	2,298	0	967	967	967	0
	16	2,298	2,298	2,298	0	967	967	967	0
	20	2,298	2,298	2,298	0	967	967	967	0
	24	2,401	2,401	2,401	0	967	967	967	0

ตารางที่ ก.5 ค่า BOD_{20} รายวัน ของสัดส่วนผสมกากตะกอน PS:SS ที่ 0:1

วันที่	ชั่วโมงที่	$TBOD_{20}$ (mg/L)				$SBOD_{20}$ (mg/L)			
	ของวัน	ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD	ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD
1	4	127	127	127	0	16.9	16.9	16.9	0
	8	212	198	205	9.9	24	24	24	0
	12	240	240	240	0	31	29.6	30.3	0.99
	16	282	268	275	9.9	38	36.6	37.3	0.99
	20	325	297	311	19.8	45.1	43.7	44.4	0.99
	24	353	325	339	19.8	52.1	52.1	52.1	0
2	4	367	339	353	19.8	57.8	57.8	57.8	0
	8	395	353	374	29.7	62	62	62	0
	12	410	381	395.5	20.51	63.4	62	62.7	0.99
	16	438	395	416.5	30.41	63.4	64.8	64.1	0.99
	20	466	410	438	39.60	66.2	67.6	66.9	0.99
	24	480	438	459	29.7	69	70.5	69.75	1.06
3	4	494	452	473	29.7	71.9	71.9	71.9	0
	8	523	452	487.5	50.2	74.7	73.3	74	0.99
	12	537	466	501.5	50.2	77.5	76.1	76.8	0.99
	16	565	494	529.5	50.2	78.9	78.9	78.9	0
	20	565	508	536.5	40.31	80.3	77.5	78.9	1.98
	24	607	537	572	49.5	81.7	78.9	80.3	1.98
4	4	621	551	586	49.5	83.1	80.3	81.7	1.98
	8	636	565	600.5	50.2	84.5	81.7	83.1	1.98
	12	650	579	614.5	50.2	86	83.1	84.55	2.05
	16	678	579	628.5	70	87.4	84.5	85.95	2.05
	20	692	593	642.5	70	87.4	86	86.7	0.99
	24	706	607	656.5	70	88.8	87.4	88.1	0.99
5	4	720	621	670.5	70	90.2	87.4	88.8	1.98
	8	734	621	677.5	79.9	91.6	88.8	90.2	1.98
	12	749	636	692.5	79.9	93	91.6	92.3	0.99
	16	763	650	706.5	79.9	93	91.6	92.3	0.99
	20	777	664	720.5	79.9	95.8	93	94.4	1.98
	24	777	664	720.5	79.9	94.4	93	93.7	0.99

ตารางที่ ก.5 ค่า BOD_{20} รายวัน ของสัดส่วนผสมกากตะกอน PS:SS ที่ 0:1 (ต่อ)

วันที่	ชั่วโมงที่ของวัน	$TBOD_{20}$ (mg/L)				$SBOD_{20}$ (mg/L)			
		ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD	ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD
6	4	791	678	734.5	79.9	97.2	94.4	95.8	1.98
	8	805	678	741.5	89.8	97.2	95.8	96.5	0.99
	12	819	692	755.5	89.8	98.6	97.2	97.9	0.99
	16	833	706	769.5	89.8	100	100	100	0
	20	833	706	769.5	89.8	101	103	102	1.41
	24	847	720	783.5	89.8	103	104	103.5	0.71
7	4	862	720	791	100.41	104	104	104	0
	8	862	734	798	90.51	104	106	105	1.41
	12	876	749	812.5	89.8	106	108	107	1.41
	16	876	749	812.5	89.8	106	108	107	1.41
	20	890	763	826.5	89.8	107	110	108.5	2.12
	24	904	777	840.5	89.8	108	110	109	1.41
8	4	890	777	833.5	79.9	108	111	109.5	2.12
	8	904	791	847.5	79.9	110	113	111.5	2.12
	12	918	791	854.5	89.8	111	114	112.5	2.12
	16	932	805	868.5	89.8	113	114	113.5	0.71
	20	932	819	875.5	79.9	111	114	112.5	2.12
	24	932	819	875.5	79.9	113	114	113.5	0.71
9	4	946	819	882.5	89.8	114	116	115	1.41
	8	946	833	889.5	79.9	116	118	117	1.41
	12	960	833	896.5	89.8	117	120	118.5	2.12
	16	974	847	910.5	89.8	117	118	117.5	0.71
	20	989	862	925.5	89.8	117	120	118.5	2.12
	24	989	876	932.5	79.9	118	121	119.5	2.12
10	4	989	876	932.5	79.9	118	123	120.5	3.54
	8	989	890	939.5	70	120	124	122	2.83
	12	1,003	904	953.5	70	120	123	121.5	2.12
	16	1,017	918	967.5	70	121	125	123	2.83
	20	932	847	889.5	60.1	121	124	122.5	2.12
	24	1,031	946	988.5	60.1	121	125	123	2.83

ตารางที่ ก.5 ค่า BOD_{20} รายวัน ของสัดส่วนผสมกากตะกอน PS:SS ที่ 0:1 (ต่อ)

วันที่	ชั่วโมงที่	$TBOD_{20}$ (mg/L)				$SBOD_{20}$ (mg/L)			
	ของวัน	ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD	ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD
11	4	1,031	960	995.5	50.2	124	127	125.5	2.12
	8	1,031	960	995.5	50.2	124	127	125.5	2.12
	12	1,945	989	1,467	675.99	124	128	126	2.83
	16	1,059	989	1,024	49.5	121	123	122	1.41
	20	1,059	1,003	1,031	39.6	124	125	124.5	0.71
	24	1,073	1,017	1,045	39.6	125	127	126	1.41
12	4	1,073	1,017	1,045	39.6	125	127	126	1.41
	8	1,073	1,031	1,052	29.7	127	128	127.5	0.71
	12	1,087	1,045	1,066	29.7	127	128	127.5	0.71
	16	1,087	1,045	1,066	29.7	127	128	127.5	0.71
	20	1,102	1,059	1,080.5	30.41	128	130	129	1.41
	24	1,102	1,059	1,080.5	30.41	128	130	129	1.41
13	4	1,116	1,073	1,094.5	30.41	128	131	129.5	2.12
	8	1,116	1,073	1,094.5	30.41	130	131	130.5	0.71
	12	1,130	1,087	1,108.5	30.41	130	132	131	1.41
	16	1,130	1,087	1,108.5	30.41	130	131	130.5	0.71
	20	1,144	1,102	1,123	29.7	131	132	131.5	0.71
	24	1,158	1,116	1,137	29.7	132	134	133	1.41
14	4	1,158	1,116	1,137	29.7	132	134	133	1.41
	8	1,158	1,116	1,137	29.7	132	135	133.5	2.12
	12	1,172	1,130	1,151	29.7	134	135	134.5	0.71
	16	1,186	1,144	1,165	29.7	134	137	135.5	2.12
	20	1,186	1,158	1,172	19.8	135	137	136	1.41
	24	1,186	1,158	1,172	19.8	135	137	136	1.41
15	4	1,186	1,172	1,179	9.9	135	137	136	1.41
	8	1,200	1,172	1,186	19.8	134	135	134.5	0.71
	12	1,200	1,186	1,193	9.9	135	138	136.5	2.12
	16	1,215	1,200	1,207.5	10.61	137	138	137.5	0.71
	20	1,229	1,215	1,222	9.9	137	139	138	1.41
	24	1,215	1,229	1,222	9.9	137	139	138	1.41

ตารางที่ ก.5 ค่า BOD_{20} รายวัน ของกากตะกอนผสมที่สัดส่วน PS:SS 0:1 (ต่อ)

วันที่	ชั่วโมงที่ของวัน	$TBOD_{20}$ (mg/L)				$SBOD_{20}$ (mg/L)			
		ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD	ซ้ำที่ 1	ซ้ำที่ 2	เฉลี่ย	±SD
16	4	1,229	1,229	1,229	0	138	141	139.5	2.12
	8	1,229	1,243	1,236	9.9	138	141	139.5	2.12
	12	1,243	1,243	1,243	0	139	141	140	1.41
	16	1,243	1,243	1,243	0	139	141	140	1.41
	20	1,257	1,257	1,257	0	139	142	140.5	2.12
	24	1,271	1,257	1,264	9.9	141	142	141.5	0.71
17	4	1,271	1,257	1,264	9.9	141	144	142.5	2.12
	8	1,285	1,271	1,278	9.9	141	144	142.5	2.12
	12	1,299	1,271	1,285	19.8	141	144	142.5	2.12
	16	1,313	1,285	1,299	19.8	142	145	143.5	2.12
	20	1,328	1,285	1,306.5	30.41	142	145	143.5	2.12
	24	1,342	1,285	1,313.5	40.31	142	145	143.5	2.12
18	4	1,342	1,299	1,320.5	30.41	142	145	143.5	2.12
	8	1,356	1,299	1,327.5	40.31	142	145	143.5	2.12
	12	1,370	1,313	1,341.5	40.31	144	147	145.5	2.12
	16	1,384	1,313	1,348.5	50.2	144	147	145.5	2.12
	20	1,398	1,313	1,355.5	60.1	144	147	145.5	2.12
	24	1,412	1,328	1,370	59.4	144	147	145.5	2.12
19	4	1,412	1,328	1,370	59.4	145	148	146.5	2.12
	8	1,441	1,328	1,384.5	79.9	145	148	146.5	2.12
	12	1,455	1,342	1,398.5	79.9	147	148	147.5	0.71
	16	1,469	1,342	1,405.5	89.8	147	148	147.5	0.71
	20	1,497	1,370	1,433.5	89.8	147	148	147.5	0.71
	24	1,525	1,384	1,454.5	99.7	147	149	148	1.41
20	4	1,525	1,384	1,454.5	99.7	148	149	148.5	0.71
	8	1,525	1,384	1,454.5	99.7	148	149	148.5	0.71
	12	1,539	1,398	1,468.5	99.7	148	151	149.5	2.12
	16	1,539	1,412	1,475.5	89.8	148	151	149.5	2.12
	20	1,539	1,412	1,475.5	89.8	149	151	150	1.41
	24	1,539	1,412	1,475.5	89.8	148	152	150	2.83

2. ผลการวัดปริมาตรก๊าซในแต่ละวันของ BMP Test

ตารางที่ ก.6 ผลการวัดปริมาตรก๊าซในแต่ละวันของ BMP Test ของสัดส่วนผสมกากตะกอน PS:SS ที่ 1:0 และ 3:1

วันที่ (day)	ปริมาณก๊าซมีเทนที่สัดส่วน 1:0 (ml)				ปริมาณก๊าซมีเทนที่สัดส่วน 3:1 (ml)			
	ซ้ำ 1	ซ้ำ 2	เฉลี่ย	สะสม	ซ้ำ 1	ซ้ำ 2	เฉลี่ย	สะสม
0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0
2	1,146	1,000	1,073	1,073	743	1,751	1,247	1,247
3	954	300	627	1,700	900	2,600	1,750	2,997
4	1,200	323	762	2,462	1,305	1,883	1,594	4,591
5	1,270	360	815	3,277	1,990	1,600	1,795	6,386
6	1,760	400	1,080	4,357	1,845	1,490	1,668	8,054
7	1,000	500	750	5,107	1,853	1,910	1,882	9,935
8	1,450	440	945	6,052	1,709	2,050	1,880	11,815
9	1,300	300	800	6,852	2,050	2,090	2,070	13,885
10	2,150	900	1,525	8,377	1,940	2,090	2,015	15,900
11	2,160	2,100	2,130	10,507	1,750	1,740	1,745	17,645
12	2,110	900	1,505	12,012	1,850	1,900	1,875	19,520
13	2,090	1,050	1,570	13,582	1,940	2,020	1,980	21,500
14	2,023	1,100	1,562	15,143	1,920	1,940	1,930	23,430
15	1,910	1,000	1,455	16,598	1,695	2,150	1,923	25,352

ตารางที่ ก.6 ผลการวัดปริมาตรก๊าซในแต่ละวันของ BMP Test ของสัดส่วนผสมกากตะกอน PS:SS ที่ 1:0 และ 3:1 (ต่อ)

วันที่ (day)	ปริมาณก๊าซมีเทนที่สัดส่วน 1:0 (ml)				ปริมาณก๊าซมีเทนที่สัดส่วน 3:1 (ml)			
	ซ้ำ 1	ซ้ำ 2	เฉลี่ย	สะสม	ซ้ำ 1	ซ้ำ 2	เฉลี่ย	สะสม
16	2,120	1,300	1,710	18,308	2,100	2,150	2,125	27,477
17	2,150	2,150	2,150	20,458	2,000	2,200	2,100	29,577
18	1,820	1,012	1,416	21,874	2,000	2,250	2,125	31,702
19	2,039	1,600	1,820	23,694	2,050	2,050	2,050	33,752
20	2,250	1,440	1,845	25,539	2,185	2,200	2,193	35,945
21	2,000	1,290	1,645	27,184	2,000	2,050	2,025	37,970
22	2,100	1,750	1,925	29,109	2,445	2,060	2,253	40,222
23	2,000	1,450	1,725	30,834	2,150	2,110	2,130	42,352
24	1,850	1,340	1,595	32,429	2,090	2,100	2,095	44,447
25	1,980	1,750	1,865	34,294	2,050	2,000	2,025	46,472
26	2,100	1,950	2,025	36,319	2,100	2,150	2,125	48,597
27	2,050	1,790	1,920	38,239	2,100	1,950	2,025	50,622
28	2,198	1,498	1,848	40,087	2,049	2,095	2,072	52,694
29	2,077	1,898	1,988	42,074	2,020	2,080	2,050	54,744
30	2,100	2,000	2,050	44,124	2,140	2,050	2,095	56,839
31	1,800	2,100	1,950	46,074	1,900	1,990	1,945	58,784

ตารางที่ ก.7 ผลการวัดปริมาตรก๊าซในแต่ละวันของ BMP Test ของสัดส่วนผสมกากตะกอน PS:SS ที่ 1:1 และ 1:3

วันที่ (day)	ปริมาณก๊าซมีเทนที่สัดส่วน 1:1 (ml)				ปริมาณก๊าซมีเทนที่สัดส่วน 1:3 (ml)			
	ซ้ำ 1	ซ้ำ 2	เฉลี่ย	สะสม	ซ้ำ 1	ซ้ำ 2	เฉลี่ย	สะสม
0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0
2	1,735	1,748	1,742	1,742	1,710	1,709	1,710	1,710
3	2,066	1,910	1,988	3,730	1,950	2,055	2,003	3,712
4	1,600	2,250	1,925	5,655	1,702	1,870	1,786	5,498
5	1,548	1,600	1,574	7,229	2,100	2,322	2,211	7,709
6	1,940	1,900	1,920	9,149	2,000	2,210	2,105	9,814
7	2,200	1,990	2,095	11,244	2,061	2,200	2,131	11,945
8	1,950	2,310	2,130	13,374	2,100	2,150	2,125	14,070
9	2,050	1,900	1,975	15,349	2,000	2,150	2,075	16,145
10	1,540	2,140	1,840	17,189	2,050	2,090	2,070	18,215
11	1,980	2,200	2,090	19,279	1,840	2,000	1,920	20,135
12	2,010	2,195	2,103	21,381	2,250	1,848	2,049	22,184
13	2,085	2,190	2,138	23,519	2,200	2,100	2,150	24,334
14	2,010	2,200	2,105	25,624	2,000	1,950	1,975	26,309
15	1,990	2,125	2,058	27,681	2,100	2,050	2,075	28,384
16	1,800	2,240	2,020	29,701	2,000	2,210	2,105	30,489
17	1,895	2,150	2,023	31,724	2,128	2,018	2,073	32,562

ตารางที่ ก.7 ผลการวัดปริมาตรก๊าซในแต่ละวันของ BMP Test ของสัดส่วนผสมกากตะกอน PS:SS ที่ 1:1 และ 1:3 (ต่อ)

วันที่ (day)	ปริมาณก๊าซมีเทนที่สัดส่วน 1:1 (ml)				ปริมาณก๊าซมีเทนที่สัดส่วน 1:3 (ml)			
	ซ้ำ 1	ซ้ำ 2	เฉลี่ย	สะสม	ซ้ำ 1	ซ้ำ 2	เฉลี่ย	สะสม
18	1,978	2,290	2,134	33,858	1,950	2,140	2,045	34,607
19	2,010	2,015	2,013	35,870	2,190	2,150	2,170	36,777
20	2,100	2,150	2,125	37,995	2,173	2,200	2,187	38,963
21	2,020	2,050	2,035	40,030	2,200	2,140	2,170	41,133
22	2,014	1,998	2,006	42,036	2,100	2,050	2,075	43,208
23	2,150	2,150	2,150	44,186	2,100	2,050	2,075	45,283
24	2,050	2,150	2,100	46,286	2,090	2,000	2,045	47,328
25	2,100	2,200	2,150	48,436	2,140	2,120	2,130	49,458
26	2,010	2,098	2,054	50,490	2,200	2,100	2,150	51,608
27	2,067	2,190	2,129	52,619	2,160	2,220	2,190	53,798
28	2,098	2,150	2,124	54,743	2,200	2,200	2,200	55,998
29	2,015	2,000	2,008	56,750	2,190	2,179	2,185	58,183
30	2,050	2,150	2,100	58,850	2,165	2,096	2,131	60,313
31	2,100	2,000	2,050	60,900	2,000	2,100	2,050	62,363

ตารางที่ ก.8 ผลการวัดปริมาตรก๊าซในแต่ละวันของ BMP Test ของสัดส่วนผสมกากตะกอน PS:SS ที่ 0:1 และ Blank

วันที่ (day)	ปริมาณก๊าซมีเทนที่สัดส่วน 0:1 (ml)				ปริมาณก๊าซมีเทนของ Blank (ml)			
	ซ้ำ 1	ซ้ำ 2	เฉลี่ย	สะสม	ซ้ำ 1	ซ้ำ 2	เฉลี่ย	สะสม
0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0
2	227	2,213	1,220	1,220	-	-	-	-
3	1,970	2,140	2,055	3,275	605	45	325	325
4	1,380	1,669	1,525	4,800	200	78	139	464
5	1,690	2,210	1,950	6,750	143	389	266	730
6	1,500	1,350	1,425	8,175	410	43	227	957
7	1,276	1,800	1,538	9,713	135	454	295	1,251
8	1,390	1,400	1,395	11,108	273	594	434	1,685
9	800	1,800	1,300	12,408	85	507	296	1,981
10	2,140	2,050	2,095	14,503	542	695	619	2,599
11	1,780	1,770	1,775	16,278	927	542	735	3,334
12	1,945	2,090	2,018	18,295	300	812	556	3,890
13	2,150	2,100	2,125	20,420	530	1,162	846	4,736
14	2,150	1,990	2,070	22,490	202	1,100	651	5,387
15	1,900	2,045	1,973	24,463	250	530	390	5,777
16	1,431	2,195	1,813	26,276	535	610	573	6,349
17	1,590	2,050	1,820	28,096	533	950	742	7,091

ตารางที่ ก.8 ผลการวัดปริมาตรก๊าซในแต่ละวันของ BMP Test ของสัดส่วนผสมกากตะกอน PS:SS ที่ 0:1 และ Blank (ต่อ)

วันที่ (day)	ปริมาณก๊าซมีเทนที่สัดส่วน 0:1 (ml)				ปริมาณก๊าซมีเทนของ Blank (ml)			
	ซ้ำ 1	ซ้ำ 2	เฉลี่ย	สะสม	ซ้ำ 1	ซ้ำ 2	เฉลี่ย	สะสม
18	1,300	1,808	1,554	29,650	1,800	830	1,315	8,406
19	1,490	1,440	1,465	31,115	1,359	1,082	1,221	9,626
20	1,860	2,150	2,005	33,120	985	1,105	1,045	10,671
21	1,540	1,250	1,395	34,515	1,200	850	1,025	11,696
22	1,780	2,155	1,968	36,482	1,012	876	944	12,640
23	1,500	1,950	1,725	38,207	1,853	659	1,256	13,896
24	1,550	2,249	1,900	40,107	1,700	864	1,282	15,178
25	1,970	2,050	2,010	42,117	1,800	820	1,310	16,488
26	2,000	2,145	2,073	44,189	450	750	600	17,088
27	2,140	2,140	2,140	46,329	260	920	590	17,678
28	2,050	2,148	2,099	48,428	1,500	954	1,227	18,905
29	1,950	1,800	1,875	50,303	1,250	876	1,063	19,968
30	2,140	2,149	2,145	52,448	1,400	912	1,156	21,124
31	2,070	2,190	2,130	54,578	1,620	912	1,266	22,390

ตารางที่ ก.9 ค่า COD และของแข็งของกากตะกอนผสมที่สัดส่วนต่าง ๆ ก่อนและหลังการทดลอง BMP Test

สัดส่วนผสม (PS:SS)	จำนวนซ้ำที่	TCOD			TS			TVS		
		Inlet (mg/L)	Outlet (mg/L)	Removal (%)	Inlet (mg/L)	Outlet (mg/L)	Removal (%)	Inlet (mg/L)	Outlet (mg/L)	Removal (%)
1:0	1	67,903.78	22,447.18	66.94	26,513	19,250	27.39	16,739.30	8,960.00	46.47
	2	67,903.78	22,447.18	66.94	26,513	19,250	27.39	16,739.30	8,960.00	46.47
	เฉลี่ย	67,903.78	22,447.18	66.94	26,513	19,250	51.66	16,739.30	8,960.00	46.47
3:1	1	52,749.14	14,524.65	72.46	24,661	10,705	56.59	14,480.40	4,420.00	69.48
	2	52,749.14	13,125.00	75.12	24,661	6,275	74.55	14,480.40	2,500.00	82.74
	เฉลี่ย	52,749.14	13,824.5	73.79	24,661	8,490	65.57	14,480.40	3,460	76.11
1:1	1	37,594.50	18,485.92	50.83	22,392	15,365	31.38	12,878.10	5,595.00	56.55
	2	37,594.50	18,485.92	50.83	22,392	15,365	31.38	12,878.10	5,595.00	56.55
	เฉลี่ย	37,594.50	18,485.92	50.83	22,392	15,365	31.38	12,878.10	7,352.5	56.55
1:3	1	22,439.86	10,408.45	53.62	18,972	15,365	19.01	10,021.40	8,680.40	13.38
	2	22,439.86	10,408.45	53.62	18,972	15,365	19.01	10,021.40	8,780.00	12.39
	เฉลี่ย	22,439.86	10,408.45	53.62	18,972	15,365	19.01	10,021.40	8,730.2	12.88
0:1	1	10,652.92	8,475.87	20.44	13,200	8,099	38.65	6,282.70	1,375.00	78.11
	2	10,652.92	8,475.87	20.44	15,825	8,099	48.82	6,282.70	1,375.00	78.11
	เฉลี่ย	10,652.92	8,475.87	20.44	14,512.5	8,099	43.74	6,282.70	1,375.00	78.11
Blank	1	252	130.91	48.05	4,540	3,015	33.59	2,000	1,860	7

ตารางที่ ก.9 ค่า COD และของแข็งของกากตะกอนผสมที่สัดส่วนต่าง ๆ ก่อนและหลังการทดลอง BMP Test (ต่อ)

สัดส่วนผสม (PS:SS)	จำนวนซ้ำที่	TCOD			TS			TVS		
		Inlet (mg/L)	Outlet (mg/L)	Removal (%)	Inlet (mg/L)	Outlet (mg/L)	Removal (%)	Inlet (mg/L)	Outlet (mg/L)	Removal (%)
Blank (ต่อ)	2	252	174.55	30.73	4,530	3,210	29.88	2,000	1,860	7
	เฉลี่ย	252	152.73	39.39	4,535	3,112.5	31.74	2,000	1,860	7

ตารางที่ ก.10 ค่า pH Alkalinity และVFA ของกากตะกอนผสมที่สัดส่วนต่าง ๆ ก่อนและหลังการทดลอง BMP Test

สัดส่วนผสม (PS:SS)	จำนวนซ้ำที่	pH		Alkalinity		VFA		VFA/Alkalinity	
		Inlet	Outlet	Inlet (mg/L)	Outlet (mg/L)	Inlet (mg/L)	Outlet (mg/L)	Inlet (mg/L)	Outlet (mg/L)
1:0	1	6.02	7.82	7,380	3,519.45	2,341.18	484.50	0.32	0.14
	2	6.02	7.68	7,380	3,519.45	2,341.18	608.96	0.32	0.17
	เฉลี่ย	6.02	7.75	7,380	3,519.45	2,341.18	546.73	0.32	0.16
3:1	1	6.26	7.70	7,311.67	5,083.65	2,045.47	502.28	0.28	0.10
	2	6.26	7.55	7,311.67	4,953.30	2,045.47	462.28	0.28	0.09
	เฉลี่ย	6.26	7.63	7,311.67	5,018.48	2,045.47	482.28	0.28	0.10
1:1	1	6.51	7.51	4,646.67	3,780.15	2,579.16	373.38	0.56	0.10
	2	6.51	7.61	4,646.67	4,562.25	2,579.16	364.49	0.56	0.08
	เฉลี่ย	6.51	7.56	4,646.67	4,171.20	2,579.16	368.93	0.56	0.09

ตารางที่ ก.10 ค่า pH Alkalinity และVFA ของกากตะกอนผสมที่สัดส่วนต่าง ๆ ก่อนและหลังการทดลอง BMP Test (ต่อ)

สัดส่วนผสม (PS:SS)	จำนวนซ้ำที่	pH		Alkalinity		VFA		VFA/Alkalinity	
		Inlet	Outlet	Inlet (mg/L)	Outlet (mg/L)	Inlet (mg/L)	Outlet (mg/L)	Inlet (mg/L)	Outlet (mg/L)
1:3	1	6.95	7.45	2,186.67	5,083.65	1,769.28	684.53	0.81	0.13
	2	6.95	7.51	2,186.67	5,344.35	1,769.28	604.52	0.81	0.11
	เฉลี่ย	6.95	7.48	2,186.67	5,214	1,769.28	644.52	0.81	0.12
0:1	1	7.46	7.92	751.67	3,519.45	1,225.20	231.14	1.63	0.07
	2	7.46	7.87	751.67	3,519.45	1,225.20	915.66	1.63	0.26
	เฉลี่ย	7.46	7.90	751.67	3,519.45	1,225.20	573.40	1.63	0.16
Blank	1	8.74	7.70	9,635	1,435.68	2,378.06	1,594.53	0.25	1.11
	2	8.70	7.68	9,635	1,416.11	2,378.06	1,584.27	0.25	1.12
	เฉลี่ย	8.72	7.69	9,635	1,425.89	2,378.06	1,589.40	0.25	1.11

3. ผลผลิตก๊าซชีวภาพการทำนายด้วยโปรแกรม SPSS ที่แบบจำลองทางจลนพลศาสตร์ต่าง ๆ

ตารางที่ ก.11 ผลผลิตก๊าซชีวภาพการทำนายด้วยโปรแกรม SPSS ที่แบบจำลองทางจลนพลศาสตร์ Modified Gompertz

วันที่ (day)	สัดส่วนผสม (PS:SS)									
	1:0		3:1		1:1		1:3		0:1	
	ปริมาณก๊าซมีเทน (ml)	$Eror^2$	ปริมาณก๊าซมีเทน (ml)	$Eror^2$	ปริมาณก๊าซมีเทน (ml)	$Eror^2$	ปริมาณก๊าซมีเทน (ml)	$Eror^2$	ปริมาณก๊าซมีเทน (ml)	$Eror^2$
0	0	0	0	0	0	0	0	0	0	0
1	445	198,435	1,519	2,307,148	1,980	3,920,479	2,164	4,684,714	1,829	3,345,680
2	694	143,831	2,179	868,456	2,771	1,059,747	3,002	1,671,409	2,500	1,638,886
3	1,028	120,159	3,000	107,669	3,733	107,906	4,014	393,719	3,303	124,623
4	1,459	290,068	3,983	20,598	4,862	107,801	5,196	26,124	4,233	10,463
5	1,991	309,036	5,122	285,669	6,146	124,129	6,532	199,371	5,281	545,958
6	2,624	602,890	6,399	486,660	7,566	392,101	8,005	726,790	6,430	620,393
7	3,353	252,567	7,796	787,994	9,097	802,368	9,588	1,221,799	7,664	635,815
8	4,170	39,006	9,288	709,806	10,712	955,350	11,254	1,278,731	8,962	212,955
9	5,060	35,895	10,846	1,119,110	12,382	972,551	12,974	1,415,267	10,302	15,750
10	6,011	54,340	12,445	731,795	14,080	260,049	14,721	800,882	11,663	57,677
11	7,004	28,727	14,058	63,827	15,779	27,622	16,467	111,663	13,028	7,012
12	8,023	9,900	15,662	1,052	17,456	1,231	18,190	10,820	14,377	792
13	9,052	42,284	17,237	223,436	19,093	95,914	19,870	74,131	15,697	162

ตารางที่ ก.11 ผลผลิตก๊าซชีวภาพการทำนายด้วยโปรแกรม SPSS ที่แบบจำลองทางจลนพลศาสตร์ Modified Gompertz (ต่อ)

วันที่ (day)	สัดส่วนผสม (PS:SS)									
	1:0		3:1		1:1		1:3		0:1	
	ปริมาณก๊าซมีเทน (ml)	Eror^2	ปริมาณก๊าซมีเทน (ml)	Eror^2	ปริมาณก๊าซมีเทน (ml)	Eror^2	ปริมาณก๊าซมีเทน (ml)	Eror^2	ปริมาณก๊าซมีเทน (ml)	Eror^2
14	10,076	102,253	18,764	519,726	20,672	188,825	21,492	324,478	16,975	16,502
15	11,084	68,691	20,230	428,933	22,180	76,165	23,042	188,860	18,201	235,274
16	12,063	10,770	21,626	247,894	23,610	66,791	24,511	138,012	19,368	312,302
17	13,005	131,305	22,943	208,502	24,955	103,942	25,894	178,827	20,470	286,139
18	13,904	189,686	24,178	776,408	26,212	577,615	27,187	971,821	21,505	68,184
19	14,755	472,230	25,327	1,443,266	27,379	1,288,588	28,389	1,533,015	22,471	966,033
20	15,554	471,392	26,392	1,251,266	28,458	1,284,913	29,500	1,459,409	23,369	847,007
21	16,301	661,148	27,373	1,209,472	29,449	1,243,849	30,523	1,179,744	24,199	1,904,759
22	16,994	276,056	28,273	478,062	30,358	924,636	31,461	797,717	24,963	1,256,193
23	17,635	485,976	29,096	409,664	31,186	803,605	32,318	866,761	25,664	1,830,582
24	18,224	947,955	29,845	332,029	31,940	692,807	33,098	899,140	26,305	1,895,688
25	18,764	919,566	30,525	293,125	32,624	457,138	33,807	700,033	26,890	1,592,114
26	19,258	752	31,141	135,225	33,243	25,380	34,448	5,138	27,422	103,317
27	19,707	728,001	31,698	1,553,613	33,801	1,298,415	35,028	1,192,115	27,905	555,845
28	20,115	1,136,782	32,199	2,528,227	34,304	2,351,745	35,551	2,377,486	28,343	1,392,424
29	20,485	2,627,868	32,650	4,519,706	34,756	4,103,866	36,022	4,807,539	28,739	2,548,397

ตารางที่ ก.11 ผลผลิตก๊าซชีวภาพการทำนายด้วยโปรแกรม SPSS ที่แบบจำลองทางจลนพลศาสตร์ Modified Gompertz (ต่อ)

วันที่ (day)	สัดส่วนผสม (PS:SS)									
	1:0		3:1		1:1		1:3		0:1	
	ปริมาณก๊าซมีเทน (ml)	$Eror^2$	ปริมาณก๊าซมีเทน (ml)	$Eror^2$	ปริมาณก๊าซมีเทน (ml)	$Eror^2$	ปริมาณก๊าซมีเทน (ml)	$Eror^2$	ปริมาณก๊าซมีเทน (ml)	$Eror^2$
30	20,819	4,756,587	33,055	7,074,802	35,162	6,572,968	36,445	7,529,152	29,096	4,962,692
31	21,120	6,571,686	33,418	8,853,898	35,526	8,902,943	36,825	9,910,345	29,418	7,671,349
sum		22,685,843		39,977,038		39,791,438		47,675,013		35,660,968
sum/n		708,932.59		1,249,282.43		1,243,482.45		1,489,844.17		1,114,405.25
NRMSE		841.98		1,117.71		1,115.12		1,220.59		1,055.65
Max		23,684.000		36,394.000		38,510.000		39,973.000		32,187.500
Min		0		0		0		0		0
NRMSE (%)		3.56		3.07		2.90		3.05		3.28

ตารางที่ ก.12 ผลผลิตก๊าซชีวภาพการทำนายด้วยโปรแกรม SPSS ที่แบบจำลองทางจลนพลศาสตร์ Modified Logistic

วันที่ (day)	สัดส่วนผสม (PS:SS)									
	1:0		3:1		1:1		1:3		0:1	
	ปริมาณก๊าซมีเทน (ml)	Eror^2	ปริมาณก๊าซมีเทน (ml)	Eror^2	ปริมาณก๊าซมีเทน (ml)	Eror^2	ปริมาณก๊าซมีเทน (ml)	Eror^2	ปริมาณก๊าซมีเทน (ml)	Eror^2
0	1,269.37	1,611,300.20	2,792.37	7,797,330.22	3,301.50	10,899,902.25	3,523.50	12,415,052.25	2,924.97	8,555,449.50
1	1,494.93	2,234,815.70	3,271.44	10,702,319.67	3,854.42	14,856,553.54	4,104.76	16,849,054.66	3,390.20	11,493,456.04
2	1,757.43	468,444.42	3,823.35	6,637,579.32	4,488.14	7,544,031.29	4,769.35	9,362,682.02	3,919.52	7,287,408.23
3	2,061.73	471,598.09	4,455.84	3,182,085.15	5,210.39	3,261,238.69	5,524.98	4,570,958.48	4,518.51	2,460,223.62
4	2,412.93	172,582.08	5,176.34	1,101,114.44	6,028.28	701,875.33	6,378.63	1,808,029.84	5,192.23	733,986.29
5	2,816.16	72,716.52	5,991.48	112,546.83	6,947.76	201,834.55	7,336.08	127,506.13	5,944.82	5,577.10
6	3,276.40	15,276.96	6,906.59	36,255.97	7,973.07	47,930.34	8,401.31	208,109.32	6,779.10	192,633.21
7	3,798.16	3,287.88	7,925.04	576,020.28	9,106.02	785,846.79	9,575.84	1,249,163.88	7,696.12	585,806.54
8	4,385.15	329.42	9,047.58	1,171,633.06	10,345.43	1,805,180.34	10,858.09	2,331,454.15	8,694.75	530,348.06
9	5,039.87	28,517.08	10,271.77	2,664,174.77	11,686.48	2,827,509.51	12,242.89	3,690,663.63	9,771.25	430,008.06
10	5,763.16	205.64	11,591.37	2,921,125.36	13,120.40	2,158,254.81	13,721.07	3,588,865.02	10,919.10	969,043.36
11	6,553.75	383,470.56	12,996.17	1,728,777.93	14,634.26	1,718,039.35	15,279.39	2,315,296.99	12,128.82	664,518.43
12	7,407.97	509,838.84	14,471.88	1,341,241.93	16,211.26	1,639,014.46	16,900.74	1,941,173.43	13,388.21	1,034,878.94
13	8,319.46	277,244.37	16,000.56	582,840.63	17,831.29	905,751.92	18,564.80	1,067,502.24	14,682.65	1,003,703.42

ตารางที่ ก.12 ผลผลิตก๊าซชีวภาพการทำนายด้วยโปรแกรม SPSS ที่แบบจำลองทางจลนพลศาสตร์ Modified Logistic (ต่อ)

วันที่ (day)	สัดส่วนผสม (PS:SS)									
	1:0		3:1		1:1		1:3		0:1	
	ปริมาณก๊าซมีเทน (ml)	$Eror^2$	ปริมาณก๊าซมีเทน (ml)	$Eror^2$	ปริมาณก๊าซมีเทน (ml)	$Eror^2$	ปริมาณก๊าซมีเทน (ml)	$Eror^2$	ปริมาณก๊าซมีเทน (ml)	$Eror^2$
14	9,279.15	227,863.02	17,561.37	231,967.46	19,471.84	585,469.83	20,248.90	453,063.61	15,995.75	1,227,110.06
15	10,275.52	298,094.16	19,131.59	197,056.09	21,109.25	632,422.56	21,929.29	459,290.84	17,310.16	1,892,935.71
16	11,294.98	440,922.56	20,687.99	193,608.80	22,720.03	399,386.08	23,582.40	310,360.41	18,608.46	1,737,229.44
17	12,322.63	1,091,753.32	22,208.11	77,500.99	24,282.20	123,060.64	25,186.18	81,122.43	19,874.05	1,279,047.90
18	13,343.08	15,730.18	23,671.58	140,685.01	25,776.44	105,261.31	26,721.22	270,628.85	21,092.03	23,094.88
19	14,341.37	75,004.78	25,061.11	874,430.71	27,186.93	889,116.98	28,171.57	1,042,583.94	22,249.78	579,547.24
20	15,303.81	190,366.42	26,363.20	1,187,446.09	28,501.84	1,387,307.07	29,525.25	1,520,905.56	23,337.42	790,178.77
21	16,218.72	534,682.69	27,568.36	1,676,662.42	29,713.46	1,902,909.89	30,774.35	1,788,505.02	24,347.97	2,339,278.48
22	17,076.86	370,101.89	28,671.15	1,186,247.72	30,817.99	2,022,055.56	31,914.88	1,814,085.73	25,277.30	2,060,086.09
23	17,871.71	872,748.32	29,669.75	1,473,189.06	31,815.07	2,325,838.50	32,946.28	2,431,354.12	26,123.91	3,286,642.67
24	18,599.41	1,819,558.19	30,565.47	1,680,834.46	32,707.25	2,557,600.56	33,870.91	2,961,531.23	26,888.55	3,841,796.00
25	19,258.57	2,111,412.42	31,362.12	1,899,214.73	33,499.25	2,406,376.56	34,693.37	2,970,004.16	27,573.80	3,784,192.09
26	19,849.88	383,631.58	32,065.30	309,469.69	34,197.41	632,677.07	35,419.87	809,766.02	28,183.64	1,172,109.37
27	20,375.76	34,128.87	32,681.84	68,727.87	34,809.04	17,281.73	36,057.69	3,882.54	28,723.01	5,185.44
28	20,839.85	116,724.72	33,219.26	324,603.67	35,341.97	245,549.98	36,614.63	228,837.86	29,197.44	105,989.31
29	21,246.62	738,533.98	33,685.33	1,189,561.05	35,804.12	956,249.29	37,098.66	1,245,098.91	29,612.73	521,673.95

ตารางที่ ก.12 ผลผลิตก๊าซชีวภาพการทำนายด้วยโปรแกรม SPSS ที่แบบจำลองทางจลนพลศาสตร์ Modified Logistic (ต่อ)

วันที่ (day)	สัดส่วนผสม (PS:SS)									
	1:0		3:1		1:1		1:3		0:1	
	ปริมาณก๊าซมีเทน (ml)	$Eror^2$	ปริมาณก๊าซมีเทน (ml)	$Eror^2$	ปริมาณก๊าซมีเทน (ml)	$Eror^2$	ปริมาณก๊าซมีเทน (ml)	$Eror^2$	ปริมาณก๊าซมีเทน (ml)	$Eror^2$
30	21,601.02	1,957,145.04	34,087.73	2,648,007.65	36,203.25	2,318,767.56	37,517.61	2,793,544.53	29,974.73	1,819,180.51
31	21,908.21	3,153,430.12	34,433.82	3,842,305.63	36,546.73	3,854,429.09	37,878.94	4,385,087.28	30,289.10	3,603,922.56
sum		20,681,460		59,756,565		72,714,723		87,095,165		66,016,241
sum/n		646,295.63		1,867,392.65		2,272,335.11		2,721,723.91		2,063,007.54
NRMSE		803.93		1,366.53		1,507.43		1,649.76		1,436.32
Max		23684		36394		38510		39973		32187.5
Min		0		0		0		0		0
NRMSE (%)		3.39		3.75		3.91		4.13		4.46

ตารางที่ ก.13 ผลผลิตก๊าซชีวภาพการทำนายด้วยโปรแกรม SPSS ที่แบบจำลองทางจลนพลศาสตร์ Pseudo First-order

วันที่ (day)	สัดส่วนผสม (PS:SS)									
	1:0		3:1		1:1		1:3		0:1	
	ปริมาณก๊าซมีเทน (ml)	$Eror^2$	ปริมาณก๊าซมีเทน (ml)	$Eror^2$	ปริมาณก๊าซมีเทน (ml)	$Eror^2$	ปริมาณก๊าซมีเทน (ml)	$Eror^2$	ปริมาณก๊าซมีเทน (ml)	$Eror^2$
0	0	0	0	0	0	0	0	0	0	0
1	1,127.86	1,272,068.18	2,054.86	4,222,449.62	2,261.54	5,114,563.17	2,349.57	5,520,479.18	1,846.04	3,407,863.68
2	2,202.01	1,274,663.58	3,993.69	7,544,305.96	4,390.27	7,015,982.51	4,561.04	8,131,280.37	3,586.21	5,598,949.76
3	3,225.01	3,422,537.00	5,823.06	9,929,179.12	6,393.99	8,937,050.46	6,642.52	10,598,410.47	5,226.58	5,182,816.50
4	4,199.30	4,847,923.24	7,549.14	11,711,042.18	8,280.04	9,545,257.41	8,601.65	12,728,126.52	6,772.86	5,940,723.77
5	5,127.18	6,659,909.26	9,177.76	12,402,793.50	10,055.33	12,651,039.65	10,445.63	12,017,523.56	8,230.47	4,888,388.34
6	6,010.88	6,816,694.37	10,714.43	13,085,799.80	11,726.36	12,491,700.61	12,181.22	11,047,114.64	9,604.48	5,695,286.79
7	6,852.50	8,982,009.00	12,164.34	12,112,766.52	13,299.26	10,934,661.70	13,814.79	9,742,451.26	10,899.69	5,944,770.48
8	7,654.04	10,804,631.96	13,532.38	11,576,189.66	14,779.79	9,552,982.82	15,352.35	8,805,166.02	12,120.61	7,277,099.71
9	8,417.40	12,576,952.96	14,823.18	8,521,611.87	16,173.37	7,870,100.84	16,799.53	6,946,018.38	13,271.51	8,091,237.14
10	9,144.42	11,336,150.29	16,041.10	7,510,888.36	17,485.12	8,384,615.18	18,161.64	6,482,828.90	14,356.41	6,016,767.47
11	9,836.81	7,095,883.72	17,190.25	8,290,080.56	18,719.83	7,699,681.53	19,443.69	6,983,810.44	15,379.08	5,929,614.61
12	10,496.23	5,636,968.09	18,274.52	6,993,486.03	19,882.03	5,714,633.68	20,650.38	5,552,526.70	16,343.11	3,754,332.51
13	11,124.25	5,190,423.06	19,297.57	6,418,976.94	20,975.98	4,809,161.28	21,786.15	4,788,000.42	17,251.84	2,456,554.68

ตารางที่ ก.13 ผลผลิตก๊าซชีวภาพการทำนายด้วยโปรแกรม SPSS ที่แบบจำลองทางจลนพลศาสตร์ Pseudo First-order (ต่อ)

วันที่ (day)	สัดส่วนผสม (PS:SS)									
	1:0		3:1		1:1		1:3		0:1	
	ปริมาณก๊าซมีเทน (ml)	$Eror^2$	ปริมาณก๊าซมีเทน (ml)	$Eror^2$	ปริมาณก๊าซมีเทน (ml)	$Eror^2$	ปริมาณก๊าซมีเทน (ml)	$Eror^2$	ปริมาณก๊าซมีเทน (ml)	$Eror^2$
14	11,722.36	3,864,605.54	20,262.86	4,927,778.42	22,005.68	3,128,228.94	22,855.15	3,737,068.92	18,108.46	1,009,944.60
15	12,291.99	2,162,340.84	21,173.65	2,554,083.42	22,974.92	1,145,798.98	23,861.32	1,573,318.66	18,915.95	52,877.00
16	12,834.49	766,482.74	22,033.01	819,043.10	23,887.23	286,471.15	24,808.35	447,360.32	19,677.12	62,190.38
17	13,351.16	267.00	22,843.85	127,699.02	24,745.97	12,762.22	25,699.71	52,308.26	20,394.65	372,527.12
18	13,843.22	140,415.08	23,608.91	97,600.01	25,554.28	10,461.20	26,538.68	114,027.78	21,071.02	29,922.08
19	14,311.85	59,706.92	24,330.78	41,934.85	26,315.12	5,058.05	27,328.34	31,627.07	21,708.60	48,444.01
20	14,758.17	11,953.05	25,011.88	68,445.02	27,031.27	85,690.85	28,071.58	48,584.98	22,309.61	19,290.43
21	15,183.23	92,580.23	25,654.54	383,111.48	27,705.38	395,163.10	28,771.13	443,382.86	22,876.15	3,323.52
22	15,588.05	775,192.20	26,260.90	1,745,305.21	28,339.89	1,115,368.33	29,429.57	1,296,022.86	23,410.21	186,442.60
23	15,973.58	929,141.77	26,833.03	2,634,031.62	28,937.14	1,830,230.18	30,049.30	1,789,441.29	23,913.63	157,902.92
24	16,340.76	827,626.87	27,372.86	3,595,346.90	29,499.32	2,587,851.34	30,632.61	2,302,472.41	24,388.18	291,945.70
25	16,690.46	1,243,314.20	27,882.20	4,417,563.24	30,028.48	3,684,557.03	31,181.63	3,198,267.26	24,835.51	628,833.14
26	17,023.50	4,870,849.00	28,362.79	9,898,637.36	30,526.57	8,268,097.68	31,698.37	7,961,595.86	25,257.19	3,399,635.32
27	17,340.68	10,367,240.83	28,816.24	17,038,402.62	30,995.40	15,563,814.01	32,184.75	15,486,192.56	25,654.69	8,977,873.62
28	17,642.76	12,522,680.79	29,244.10	20,656,116.01	31,436.71	19,366,952.62	32,642.53	19,806,683.22	26,029.39	12,205,310.83
29	17,930.45	17,435,217.80	29,647.79	26,298,537.80	31,852.09	24,304,012.61	33,073.41	26,430,806.39	26,382.59	15,621,544.81

ตารางที่ ก.13 ผลผลิตก๊าซชีวภาพการทำนายด้วยโปรแกรม SPSS ที่แบบจำลองทางจลนพลศาสตร์ Pseudo First-order (ต่อ)

วันที่ (day)	สัดส่วนผสม (PS:SS)									
	1:0		3:1		1:1		1:3		0:1	
	ปริมาณก๊าซมีเทน (ml)	Eror^2	ปริมาณก๊าซมีเทน (ml)	Eror^2	ปริมาณก๊าซมีเทน (ml)	Eror^2	ปริมาณก๊าซมีเทน (ml)	Eror^2	ปริมาณก๊าซมีเทน (ml)	Eror^2
30	18,204.44	22,997,395.71	30,028.69	32,334,121.42	32,243.09	30,062,302.07	33,478.96	32,604,556.80	26,715.54	21,233,295.36
31	18,465.39	27,233,890.33	30,388.08	36,071,075.05	32,611.12	34,796,785.25	33,860.68	37,360,455.78	27,029.40	26,605,995.61
sum		192,217,716		284,028,403		257,371,036		264,027,910		161,091,704
sum/n		6,006,803.61		8,875,887.58		8,042,844.89		8,250,872.19		5,034,115.77
NRMSE		2,450.88		2,979.24		2,835.99		2,872.43		2,243.68
Max		23,684.00		36,394.00		38,510.00		39,973.00		32,187.50
Min		0		0		0		0		0
NRMSE (%)		10.35		8.19		7.36		7.19		6.97

4. รูปภาพชุดทดลอง

รูปที่ ก.1 การวิเคราะห์ BOD_{20} โดยเครื่อง Oxitop

รูปที่ ก.2 ชุดทดลอง BMP Test

ภาคผนวก ข

การติดตั้งระบบ Two-stage CSTR

1. รายการคำนวณการออกแบบชุดทดลองระบบ Two-stage CSTR

ตารางที่ ข.1 ค่าการเดินระบบ Two-stage CSTR

พารามิเตอร์	สภาวะเดินระบบ	
	CSTR 1	CSTR 2
Feed	สัดส่วนผสมกากตะกอน PS:SS ที่ 1:3	Effluent CSTR 1
Volume reactor (L)	3	22.5
Dimeter (cm)	15.24 (6”)	15.24 (6”)
Height (cm)	19	126.81
HRT (d)	1.6	24
Operating days (d)	220	
OLR (kg VS/m^3-day)	0.44	

<u>รายการคำนวณ</u>

กำหนดให้ เดินระบบเป็นแบบ Semi-continuous Feed และใน 1 วัน มีระยะเวลาทำปฏิกิริยา 21 hr ระยะเวลาพักตกตะกอน 2 hr และระยะเวลาเดรนน้ำเข้า-ออก 1 hr

- CSTR 1

COD fed = 42,019 mg/L

TVS_{fed} (mg/L) = 10,641 mg/L

V = 3 L

HRT = 1.6 d

$OLR_{ระบบ}$ = COD/HRT or TVS/HRT

$$= \frac{42{,}019\ \text{mg COD/L}}{25.6\ \text{d}} \times \frac{1\ \text{kg}}{1{,}000{,}000\ \text{mg}} \times \frac{1{,}000\ \text{L}}{1\ \text{m}^3}$$

= 1.64 kg COD/m^3-d

$$= \frac{10{,}641\ \text{mg COD/L}}{25.6\ \text{d}} \times \frac{1\ \text{kg}}{1{,}000{,}000\ \text{mg}} \times \frac{1{,}000\ \text{L}}{1\ \text{m}^3}$$

= 0.44 kg VS/m^3-d

$L_{in,out}$/day = Q x t

$$= \frac{3\ \text{L}}{1.6\ \text{d}} \times \frac{21\ \text{hr}}{1\ \text{d}} \times \frac{1\ \text{d}}{24\ \text{hr}}$$

$L_{in,out}$/day	=	1.641	L/day
กำหนด ขนาดถัง (ท่อ PVC)	=	6	inch
	=	0.1524	m
Ø ใน	=	153.3	mm
	=	0.1533	m
Ø นอก	=	165	mm
	=	0.165	m
ความหนา	=	11.7	mm
	=	0.0117	m
จาก V ทรงกระบอก	=	$\pi r^2 h$	
จะได้ ความสูงของระดับน้ำ	=	$(V \times 4)/(\pi Ø^2)$	
	=	$\frac{(3\ L \times 4)}{\pi \times (0.1533\ m)^2} \times \frac{1\ m^3}{1,000\ L}$	
	=	0.1626	m
	=	16.262	cm
Freebord	=	$50\% \times (V_{biogas/day\ @HRT\ 1.6\ d} \times 4)/(\pi Ø^2)$	
	=	$\frac{0.5 \times (4 \times (0.1710\ L))}{(\pi \times (0.1533\ m)^2)} \times \frac{1\ m^3}{1,000\ L}$	
(50% Biogas Production)	=	0.00463	m
	=	0.46	cm
H รวม	=	16.262 cm + 0.463	cm
	=	16.73	cm
กำหนด ขนาดใบกวน			
กว้าง	=	2	cm
ยาว	=	7	cm

- CSTR 2

V	=	22.5	L
HRT	=	24	d
$L_{in,out}$/day	=	Q x t	

	$L_{in,out}$/day	=	$\frac{22.5\ L}{24\ d} \times \frac{21\ hr}{1\ d} \times \frac{1\ d}{24\ hr}$	
		=	0.820	L/day
กำหนด	ขนาดถัง (ท่อ PVC)	=	6	inch
		=	0.1524	m
	Ø ใน	=	153.3	mm
		=	0.1533	m
	Ø นอก	=	165	mm
		=	0.165	m
	ความหนา	=	11.7	mm
		=	0.0117	m
จาก	V ทรงกระบอก	=	$\pi r^2 h$	
จะได้	ความสูงของระดับน้ำ	=	$(V \times 4)/(\pi Ø^2)$	
		=	$\frac{(22.5\ L \times 4)}{\pi \times (0.1533\ m)^2} \times \frac{1\ m^3}{1{,}000\ L}$	
		=	1.2196	m
		=	121.963	cm
	Freebord	=	$50\% \times (V_{biogas/day\ @HRT\ 24\ d} \times 4)/(\pi Ø^2)$	
		=	$\frac{0.5 \times (4 \times (2.045\ L))}{(\pi \times (0.1533\ m)^2)} \times \frac{1\ m^3}{1{,}000\ L}$	
(50% Biogas Production)		=	0.0554	m
		=	5.54	cm
	H รวม	=	121.963 cm + 5.54	cm
		=	127.50	cm
ดังนั้น	ใช้ท่อ 6 “ ทั้ง 2 ถังรวม	=	16.73 cm + 127.50	cm
		=	144.23	cm

2. รายละเอียดอุปกรณ์ชุดทดลองระบบ Two-stage CSTR

ตารางที่ ข.2 รายละเอียดอุปกรณ์ชุดทดลองระบบ Two-stage CSTR

รายการ	ขนาด	จำนวน	
		ปริมาณ	หน่วย
1. ท่อ PVC ชั้น 13.5	6 นิ้ว	1	ท่อน (4 เมตร/ท่อน)
2. ท่อสั้นหน้าแปลน PVC	6 นิ้ว	4	ชิ้น
3. ประเก็นยาง	6 นิ้ว	4	ชิ้น
4. หน้าแปลนตาบอด PVC หนา 20 มม.	6 นิ้ว	4	ชิ้น
5. Gas Counter	-	2	เครื่อง
6. ปั๊ม	-	3	เครื่อง
7. มอเตอร์กวน AC (เพลา 7 mm)	14W, 60 rpm	1	ชิ้น
8. แกนพร้อมใบกวนสแตนเลส	2*7 cm	1	ชิ้น
9. สายยางซิลิโคน	7*9 mm	10	เมตร
10. ก๊อกพลาสติก	½”	4	ชิ้น
11. เช็ควาล์วพลาสติก	ID 5.86 mm	11	ชิ้น
12. ชุดน๊อตสกรูสแตนเลสสำหรับยึดหน้าแปลน	M20 x 80	32	ชุด

ภาคผนวก ค

ผลการเดินระบบ Two-stage CSTR

1. ผลการเกิดก๊าซชีวภาพของระบบ Two-stage CSTR

ตารางที่ ค.1 ผลการเกิดก๊าซชีวภาพของระบบ Two-stage CSTR

วันที่	ปริมาณก๊าซชีวภาพรายวัน (ml)		วันที่	ปริมาณก๊าซชีวภาพรายวัน (ml)	
	CSTR 1	CSTR 2		CSTR 1	CSTR 2
0 - 34	0	0	63	0	2,108
35	0	68	64	0	1,428
36	0	68	65	0	2,040
37	0	68	66	0	1,904
38	0	68	67	0	1,768
39	0	612	68	0	2,992
40	0	204	69	0	2,924
41	0	136	70	0	2,516
42	0	204	71	0	2,652
43	0	68	72	0	2,108
44	0	204	73	0	2,040
45	0	204	74	0	1,428
46	0	238	75	0	2,312
47	0	272	76	0	1,632
48	0	68	77	0	1,904
49	0	238	78	0	2,720
50	0	408	79	0	2,720
51	0	68	80	0	2,380
52	0	204	81	0	1,768
53	0	170	82	0	1,836
54	0	136	83	0	1,224
55	0	340	84	0	1,360
56	0	272	85	0	952
57	0	544	86	0	748
58	0	408	87	0	1,088
59	0	680	88	0	544
60	0	1,224	89	0	680
61	0	1,496	90	0	476
62	0	1,632	91	0	612

ตารางที่ ค.1 ผลการเกิดก๊าซชีวภาพของระบบ Two-stage CSTR (ต่อ)

วันที่	ปริมาณก๊าซชีวภาพรายวัน (ml)		วันที่	ปริมาณก๊าซชีวภาพรายวัน (ml)	
	CSTR 1	CSTR 2		CSTR 1	CSTR 2
92	0	544	123	0	1,632
93	0	816	124	0	1,564
94	0	748	125	0	1,700
95	0	748	126	0	1,496
96	0	680	127	0	1,972
97	0	476	128	0	952
98	0	748	129	0	1,088
99	0	612	130	0	1,156
100	0	1,564	131	0	990
101	0	1,564	132	0	540
102	0	476	133	0	585
103	0	884	134	0	630
104	0	1,292	135	0	540
105	0	952	136	0	270
106	0	1,564	137	0	540
107	0	2,584	138	0	900
108	0	1,428	139	0	630
109	0	2,924	140	0	360
110	0	2,924	141	0	360
111	0	2,652	142	0	810
112	0	2,380	143	0	720
113	0	2,856	144	0	270
114	0	2,448	145	0	270
115	0	1,904	146	0	180
116	0	3,060	147	0	450
117	0	2,652	148	0	630
118	0	2,176	149	0	450
119	0	1,564	150	0	450
120	0	1,360	151	0	360
121	0	1,496	152	0	270
122	0	1,496	153	0	450

ตารางที่ ค.1 ผลการเกิดก๊าซชีวภาพของระบบ Two-stage CSTR (ต่อ)

วันที่	ปริมาณก๊าซชีวภาพรายวัน (ml)		วันที่	ปริมาณก๊าซชีวภาพรายวัน (ml)	
	CSTR 1	CSTR 2		CSTR 1	CSTR 2
154	0	150	185	0	450
155	0	450	186	0	360
156	0	270	187	0	450
157	0	450	188	0	360
158	0	450	189	0	450
159	0	450	190	0	360
160	0	180	191	0	450
161	0	450	192	0	450
162	0	720	193	0	450
163	0	360	194	0	450
164	0	90	195	0	450
165	0	360	196	0	270
166	0	270	197	0	540
167	0	270	198	0	450
168	0	450	199	0	630
169	0	360	200	0	450
170	0	450	201	0	360
171	0	360	202	0	450
172	0	450	203	0	360
173	0	360	204	0	450
174	0	450	205	0	360
175	0	450	206	0	450
176	0	450	207	0	450
177	0	450	208	0	450
178	0	450	209	0	450
179	0	270	210	0	450
180	0	540	211	0	270
181	0	450	212	0	540
182	0	630	213	0	450
183	0	360	214	0	630
184	0	450	215	0	450

ตารางที่ ค.1 ผลการเกิดก๊าซชีวภาพของระบบ Two-stage CSTR (ต่อ)

วันที่	ปริมาณก๊าซชีวภาพรายวัน (ml)		วันที่	ปริมาณก๊าซชีวภาพรายวัน (ml)	
	CSTR 1	CSTR 2		CSTR 1	CSTR 2
216	0	450	219	0	270
217	0	450	220	0	540
218	0	450			

2. ประสิทธิภาพการกำจัดค่า TVS ของระบบ Two-stage CSTR

ตารางที่ ค.2 ประสิทธิภาพการกำจัดค่า TVS ของระบบ Two-stage CSTR

วันที่	TVS (mg/L)			Efficiency
	Influent	Effluent CSTR 1	Effluent CSTR 2	
1	6,980	1,000	210	96.99
2	2,050	1,080	550	93.73
3	1,500	880	565	93.70
4	6,795	1,105	430	93.67
5	7,140	1,055	680	90.48
6	4,650	920	120	97.42
7	5,615	795	125	97.77
8	7,780	975	420	94.60
9	9,375	3,240	655	93.01
10	10,490	5,175	555	94.71
11	9,255	4,627	455	95.08
12	8,020	4,080	290	96.38
13	4,730	4,060	610	87.10
14	3,060	2,685	230	92.48
15	3,225	665	515	84.03
16	4,465	3,235	315	92.95
17	5,090	815	360	92.93
18	5,150	2,745	570	88.93
19	3,020	2,390	335	88.91
20	6,990	3,615	725	89.63
21	6,980	4,025	615	91.19
22	15,840	4,902	565	96.43

ตารางที่ ค.2 ประสิทธิภาพการกำจัดค่า TVS ของระบบ Two-stage CSTR (ต่อ)

วันที่	TVS (mg/L)			Efficiency
	Influent	Effluent CSTR 1	Effluent CSTR 2	
23	25,695	5,780	515	98.00
25	6,235	5,105	755	87.89
27	7,655	6,165	655	91.44
28	5,090	2,875	1,340	92.83
31	13,220	11,025	765	94.21
37	21,350	18,600	800	96.25
40	17,453	1,070	465	97.34
43	13,555	4,305	725	94.65
46	9,658	7,905	610	94.16
49	5,760	450	365	93.66
52	20,205	19,370	1,090	94.61
55	21,040	3,215	1,315	93.75
58	19,621	12,355	1,090	94.44
61	18,202	16,610	1,110	93.90
64	20,445	20,445	450	97.80
67	15,365	3,405	695	95.48
71	15,680	10,095	325	97.93
73	15,995	15,995	940	94.12
77	23,110	23,110	520	97.75
79	14,965	5,355	820	94.52
82	9,295	2,290	420	95.13
85	10,203	2,040	435	95.74
87	9,749	1,790	450	95.38
90	9,522	1,300	510	94.64
93	9,295	7,880	590	95.68
96	10,657	2,890	350	96.72
99	12,020	3,700	640	94.68
102	12,020	3,190	510	95.76
105	12,020	6,870	510	95.76
108	12,020	11,810	150	98.75

ตารางที่ ค.2 ประสิทธิภาพการกำจัดค่า TVS ของระบบ Two-stage CSTR (ต่อ)

วันที่	TVS (mg/L)			Efficiency
	Influent	Effluent CSTR 1	Effluent CSTR 2	
110	12,020	10,450	590	95.09
113	14,920	11,810	1,165	94.57
115	14,965	11,810	760	94.32
118	17,082	14,990	1,015	94.06
122	18,141	16,775	737	95.93
125	19,200	18,560	460	97.60
127	14,325	10,450	220	98.46
130	9,450	2,340	420	95.56
133	5,200	660	210	95.96
136	6,560	2,850	350	94.66
139	7,920	2,025	450	94.32
140	9,280	1,200	390	95.80
142	10,640	1,860	390	96.33
145	10,640	1,780	390	96.33
148	9,289	2,040	110	98.82
151	7,938	2,840	215	97.29
152	8,694	1,250	320	96.32
156	9,072	3,750	200	97.80
159	9,450	1,430	70	99.26
162	6,990	3,011	515	92.63
165	6,980	1,411	615	91.19
168	6,235	669	335	94.63
171	7,655	753	360	95.30
174	12,295	874	515	95.81
177	7,110	1,068	610	91.42
180	9,295	796	455	95.10
183	7,933	6,143	655	91.74
186	6,570	640	125	98.10
189	5,200	2,297	520	90.00
192	9,450	1,962	565	94.02
195	14,325	2,008	210	98.53

ตารางที่ ค.2 ประสิทธิภาพการกำจัดค่า TVS ของระบบ Two-stage CSTR (ต่อ)

วันที่	TVS (mg/L)			Efficiency
	Influent	Effluent CSTR 1	Effluent CSTR 2	
198	14,920	2,992	550	96.31
201	7,655	1,170	430	94.38
204	15,840	1,826	120	99.24
207	15,840	1,411	420	97.35
210	10,640	1,036	555	94.78
213	12,020	5,309	290	97.59

3. ประสิทธิภาพการกำจัด COD ของระบบ Two-stage CSTR

ตารางที่ ค.3 ประสิทธิภาพการกำจัด COD ของระบบ Two-stage CSTR

วันที่	Influent		Effluent CSTR 1		Effluent CSTR 2		Efficiency	
	TCOD (mg/L)	SCOD (mg/L)	TCOD (mg/L)	SCOD (mg/L)	TCOD (mg/L)	SCOD (mg/L)	TCOD (mg/L)	SCOD (mg/L)
1	28,571.43	25,000.00	40,145.99	21,897.81	25,547.45	7,299.27	29.76	52.88
5	34,358.71	23,448.91	40,145.99	21,897.81	25,547.45	7,299.27	25.64	68.87
7	39,651.26	23,735.96	44,943.82	22,471.91	26,217.23	14,981.27	33.88	36.88
10	28,571.43	25,000.00	25,000.00	17,857.14	14,285.71	3,571.43	50.00	85.71
13	25,000.00	19,642.86	21,428.57	14,285.71	14,285.71	7,142.86	42.86	63.64
17	29,675.57	20,501.64	25,000.00	14,285.71	21,428.57	10,714.29	27.79	47.74
19	34,351.15	26,717.56	26,717.56	15,267.18	22,900.76	7,633.59	33.33	71.43
22	32,442.75	24,809.16	30,534.35	22,900.76	22,900.76	15,267.18	29.41	38.46
25	29,962.55	14,981.27	14,981.27	7,490.64	11,235.96	3,745.32	62.50	75.00
28	69,288.39	36,816.48	67,415.73	37,453.18	11,235.96	7,490.64	83.78	79.65
31	46,816.48	21,835.21	22,471.91	7,490.64	14,981.27	3,745.32	68.00	82.85
37	71,161.05	36,179.78	26,217.23	22,471.91	14,981.27	7,490.64	78.95	79.30
40	65,320.30	40,394.72	59,479.55	44,609.67	29,739.78	22,304.83	54.47	44.78
43	46,468.40	40,892.19	44,609.67	37,174.72	40,892.19	22,304.83	12.00	45.45
44	48,327.14	44,609.67	48,327.14	44,609.67	29,739.78	22,304.83	38.46	50.00
49	48,327.14	37,174.72	48,327.14	22,304.83	33,457.25	7,434.94	30.77	80.00

ตารางที่ ค.3 ประสิทธิภาพการกำจัด COD ของระบบ Two-stage CSTR (ต่อ)

วันที่	Influent		Effluent CSTR 1		Effluent CSTR 2		Efficiency	
	TCOD (mg/L)	SCOD (mg/L)	TCOD (mg/L)	SCOD (mg/L)	TCOD (mg/L)	SCOD (mg/L)	TCOD (mg/L)	SCOD (mg/L)
52	78,066.91	46,468.40	78,066.91	70,631.97	37,174.72	7,434.94	52.38	84.00
55	70,631.97	45,762.08	63,197.03	33,457.25	26,022.30	7,434.94	63.16	83.75
58	55,315.99	38,119.14	34,285.71	15,238.10	19,047.62	15,238.10	65.57	60.03
61	40,000.00	30,476.19	36,190.48	30,476.19	34,285.71	22,857.14	14.29	58.65
64	43,809.52	30,476.19	38,095.24	22,857.14	30,476.19	22,857.14	30.43	58.65
67	49,523.81	38,095.24	47,619.05	26,666.67	22,857.14	15,238.10	53.85	60.00
71	40,000.00	35,238.10	30,476.19	35,238.10	26,666.67	19,047.62	33.33	45.95
73	50,476.19	32,380.95	50,476.19	32,380.95	30,476.19	22,857.14	39.62	29.41
77	60,952.38	29,047.62	60,952.38	22,857.14	15,238.10	11,428.57	75.00	60.66
79	34,285.71	26,666.67	19,047.62	15,238.10	15,238.10	11,428.57	55.56	57.14
82	39,484.78	25,136.61	37,064.79	19,422.33	23,356.75	11,615.93	40.85	53.79
87	44,683.84	23,606.56	55,081.97	23,606.56	31,475.41	11,803.28	29.56	50.00
90	55,081.97	25,409.84	55,081.97	33,442.62	27,540.98	15,737.70	50.00	38.06
93	55,081.97	27,213.11	55,081.97	43,278.69	27,540.98	9,836.07	50.00	63.86
96	62,086.44	26,666.67	19,672.13	15,737.70	26,594.92	3,934.43	57.16	85.25
99	69,090.91	17,272.73	18,181.82	10,909.09	10,909.09	3,636.36	84.21	78.95
102	54,698.13	22,324.89	32,977.10	25,648.85	25,648.85	14,656.49	53.11	34.35
105	47,501.73	27,377.05	21,984.73	7,328.24	18,320.61	3,664.12	61.43	86.62

ตารางที่ ค.3 ประสิทธิภาพการกำจัด COD ของระบบ Two-stage CSTR (ต่อ)

วันที่	Influent		Effluent CSTR 1		Effluent CSTR 2		Efficiency	
	TCOD (mg/L)	SCOD (mg/L)	TCOD (mg/L)	SCOD (mg/L)	TCOD (mg/L)	SCOD (mg/L)	TCOD (mg/L)	SCOD (mg/L)
108	40,305.34	18,320.61	29,312.98	14,656.49	25,648.85	10,992.37	36.36	40.00
110	47,693.66	22,930.80	28,426.98	19,131.52	21,984.73	14,656.49	53.90	36.08
113	55,081.97	27,540.98	27,540.98	23,606.56	27,540.98	19,672.13	50.00	28.57
115	47,272.73	18,181.82	21,818.18	7,272.73	10,909.09	3,636.36	76.92	80.00
118	51,177.35	22,861.40	14,545.45	14,545.45	18,181.82	14,545.45	64.47	36.38
121	41,952.31	20,521.61	23,636.36	9,090.91	21,818.18	11,090.91	47.99	45.95
125	32,727.27	18,181.82	32,727.27	3,636.36	25,454.55	7,636.36	22.22	58.00
128	31,493.51	17,337.66	30,259.74	5,584.42	22,900.43	6,632.03	27.29	61.75
131	30,259.74	16,493.51	27,792.21	7,532.47	20,346.32	7,627.71	32.76	53.75
134	29,951.30	16,282.47	35,411.26	9,437.23	24,155.84	7,627.71	19.35	53.15
137	28,871.75	15,543.83	29,134.20	10,432.90	19,696.97	7,623.38	31.78	50.96
140	27,792.21	14,805.19	22,857.14	11,428.57	15,238.10	7,619.05	45.17	48.54
143	27,175.32	14,383.12	38,095.24	15,238.10	22,857.14	7,619.05	15.89	47.03
146	22,857.14	11,428.57	15,238.10	11,428.57	7,619.05	3,809.52	66.67	66.67
149	22,857.14	11,428.57	22,857.14	19,047.62	19,047.62	3,809.52	16.67	66.67
152	22,857.14	11,428.57	15,238.10	15,238.10	15,238.10	3,809.52	33.33	66.67
155	55,081.97	27,213.11	55,081.97	43,278.69	27,540.98	13,606.56	50.00	50.00
158	51,177.35	22,697.47	38,450.07	25,275.71	19,225.04	9,621.46	62.43	57.61

ตารางที่ ค.3 ประสิทธิภาพการกำจัด COD ของระบบ Two-stage CSTR (ต่อ)

วันที่	Influent		Effluent CSTR 1		Effluent CSTR 2		Efficiency	
	TCOD (mg/L)	SCOD (mg/L)	TCOD (mg/L)	SCOD (mg/L)	TCOD (mg/L)	SCOD (mg/L)	TCOD (mg/L)	SCOD (mg/L)
161	49,225.04	20,439.64	30,134.13	16,274.22	15,067.06	7,628.91	69.39	62.68
164	47,272.73	18,181.82	21,818.18	7,272.73	10,909.09	5,636.36	76.92	69.00
167	42,402.60	17,337.66	22,077.92	8,311.69	11,991.34	6,132.03	71.72	64.63
170	37,532.47	16,493.51	22,337.66	9,350.65	13,073.59	6,627.71	65.17	59.82
173	30,715.35	17,388.05	26,409.06	13,427.01	14,389.93	8,618.27	53.15	50.44
176	27,792.21	14,805.19	22,857.14	11,428.57	15,238.10	7,619.05	45.17	48.54
179	30,715.35	17,388.05	26,409.06	13,427.01	14,389.93	8,618.27	53.15	50.44
182	33,638.49	19,970.90	29,960.97	15,425.45	13,541.76	9,617.49	59.74	51.84
185	36,561.64	22,553.76	33,512.88	17,423.89	12,693.60	10,616.71	65.28	52.93
188	39,484.78	25,136.61	37,064.79	19,422.33	11,845.43	11,615.93	70.00	53.79
191	37,178.52	22,975.84	34,746.65	16,449.86	19,693.21	10,118.87	47.03	55.96
194	34,872.26	20,815.06	32,428.50	13,477.40	27,540.98	8,621.82	21.02	58.58
197	32,566.00	18,654.28	30,110.35	10,504.93	20,276.34	7,124.76	37.74	61.81
200	30,259.74	16,493.51	27,792.21	7,532.47	13,011.69	5,627.71	57.00	65.88
203	37,471.79	20,050.03	41,437.09	15,569.51	14,548.94	8,715.49	61.17	56.53
206	37,471.79	20,050.03	41,437.09	15,569.51	14,548.94	8,715.49	61.17	56.53
209	44,683.84	23,606.56	55,081.97	23,606.56	16,086.18	11,803.28	64.00	50.00
212	41,000.71	21,775.53	50,164.29	20,064.23	22,857.14	10,259.39	44.25	52.89

ตารางที่ ค.3 ประสิทธิภาพการกำจัด COD ของระบบ Two-stage CSTR (ต่อ)

วันที่	Influent		Effluent CSTR 1		Effluent CSTR 2		Efficiency	
	TCOD (mg/L)	SCOD (mg/L)	TCOD (mg/L)	SCOD (mg/L)	TCOD (mg/L)	SCOD (mg/L)	TCOD (mg/L)	SCOD (mg/L)
215	37,317.57	19,944.51	45,246.61	16,521.89	15,381.16	8,715.49	58.78	56.30
218	33,634.43	18,113.49	40,328.93	12,979.56	15,028.65	7,171.60	55.32	60.41
221	29,951.30	16,282.47	35,411.26	9,437.23	14,676.14	5,627.71	51.00	65.44

4. ค่า pH ของระบบ Two-stage CSTR

ตารางที่ ค.4 ค่า pH ของระบบ Two-stage CSTR

วันที่	pH			วันที่	pH		
	Influent	CSTR 1	CSTR 2		Influent	CSTR 1	CSTR 2
2	6.83	7.2	7.25	32	6.63	7.04	7.03
3	6.69	7.26	7.25	34	6.87	6.70	7.15
4	6.7	7.2	7.49	38	7.24	6.67	7.10
5	6.68	6.96	7.57	39	6.91	6.9	7.08
6	6.83	7.23	7.5	40	6.96	6.87	7.09
7	6.74	7.17	7.35	41	6.97	6.9	7.08
8	6.84	7.13	7.51	42	6.97	6.9	7.16
9	6.94	7.09	7.4	44	6.7	7.05	7.17
10	7.01	7.02	7.45	45	6.77	7.05	7.26
11	6.86	6.78	7.33	50	6.84	6.94	7.58
12	7.58	7.25	7.3	53	6.9	6.92	7.36
13	6.98	6.97	7.38	55	6.94	6.8	7.57
14	6.95	6.96	7.34	56	6.98	6.65	7.25
15	7.04	7.08	7.32	59	6.83	6.9	7.25
16	7.08	7.1	7.3	60	6.85	6.9	7.09
17	7.12	7.33	7	62	6.87	6.9	7.49
18	7.11	7.04	7.37	63	6.8	6.9	7.09
19	7.08	7	7.3	65	6.89	6.9	7.13
20	6.94	6.71	7.28	68	6.98	6.9	7.01
21	6.96	6.78	7.28	70	6.85	6.9	6.98
22	6.97	6.79	7.33	72	6.9	6.9	7
23	6.85	6.79	7.3	73	6.9	6.9	6.96
24	6.64	6.7	7.22	74	6.95	6.9	7.02
25	6.96	6.8	7.16	76	7	6.9	7.21
26	7.01	6.86	7.19	78	7	6.9	7.09
27	6.95	6.76	7.15	79	7.05	6.9	7.19
28	7.04	6.72	7.01	80	7.04	6.69	7.18
29	6.94	6.93	7.01	83	6.84	7.07	7.02
30	6.91	6.7	6.91	85	6.83	6.94	7.25

ตารางที่ ค.4 ค่า pH ของระบบ Two-stage CSTR (ต่อ)

วันที่	pH			วันที่	pH		
	Influent	CSTR 1	CSTR 2		Influent	CSTR 1	CSTR 2
88	6.88	6.86	7.02	155	6.95	7.14	7.46
90	6.84	6.95	7.1	157	6.62	6.93	7.44
91	7.07	7	7.12	160	6.79	6.92	7.41
94	7.01	6.84	7.11	162	6.95	6.9	7.38
95	6.9	6.9	7.12	167	6.98	6.97	7.36
97	6.91	6.85	7.02	169	7.07	6.97	7.25
100	6.77	6.75	7.08	173	7.23	7.03	7.53
103	6.79	6.9	7.03	176	7.05	6.9	7.38
105	6.81	6.9	6.99	180	7.02	6.73	7.31
106	6.71	6.9	6.96	182	7.12	7.15	7.33
109	6.86	6.9	6.97	184	7.07	6.9	7.27
110	6.81	6.9	7.05	185	7.15	7.18	7.33
111	6.88	6.9	7.25	187	7.16	6.9	7.29
114	6.76	6.9	7.25	190	7.17	6.9	7.25
116	6.95	6.9	7.25	191	7.24	7.22	7.45
119	6.99	6.88	6.93	193	7.19	6.9	7.48
120	6.915	6.76	7.25	194	7.18	7.2	7.39
121	6.84	6.64	6.94	197	6.98	6.94	7.38
122	6.825	6.77	6.93	199	6.98	7.2	7.41
125	6.8175	6.835	6.96	200	7.16	6.9	7.3
126	6.81	6.9	6.93	202	7.2	7.165	7.42
128	6.89	6.73	7.06	204	7.24	6.98	7.54
131	6.87	7.17	7.18	206	7.175	6.975	7.58
134	6.93	7.15	7.21	208	7.11	6.97	7.25
137	6.98	7.13	7.24	211	6.98	7.13	7.25
141	7.07	7.16	7.28	212	6.98	7.04	7.47
143	7.25	7.18	7.31	214	6.98	6.9	7.51
145	7.22	7.15	7.32	215	6.98	7.12	7.48
147	7.18	7.12	7.33	216	7.16	7.2	7.45
149	7.23	7.24	7.41	217	6.98	7.17	7.55
152	7.27	6.9	7.48	218	7.22	7.16	7.41

5. ค่า VFA/Alkalinity ของระบบ Two-stage CSTR

ตารางที่ ค.5 ค่า VFA และ Alkalinity ของระบบ Two-stage CSTR

วันที่	Alkalinity (mg/L as $CaCO_3$)			VFA (mg/L as mg/L as CH_3COOH)			VFA/Alkalinity		
	Feed	CSTR 1	CSTR 2	Feed	CSTR 1	CSTR 2	Feed	CSTR 1	CSTR 2
1	1,265	1,361	1,093	1,164.34	664.44	84.23	0.92	0.49	0.08
4	1,265	1,361	1,093	1,164.34	464.05	21.09	0.92	0.34	0.02
9	1,265	1,361	1,093	1,427.15	506.24	107.62	1.13	0.37	0.10
14	1,265	1,361	1,093	1,345.27	548.42	109.68	1.06	0.40	0.10
19	1,265	1,361	1,093	1,304.33	1,062.66	162.46	1.03	0.78	0.15
20	1,427	1,369	1,045	1,263.38	1,576.89	215.24	0.89	1.15	0.21
23	1,508	1,373	1,021	2,255.37	1,066.85	280.75	1.50	0.78	0.27
24	1,589	1,377	997	1,696.21	1,293.80	264.38	1.07	0.94	0.27
27	1,480	1,129	952	1,137.04	1,520.74	248.00	0.77	1.35	0.26
29	1,371	881	906	1,438.85	1,965.88	172.96	1.05	2.23	0.19
33	1,407	1,281	1,028	1,740.66	1,745.34	238.64	1.24	1.36	0.23
34	1,442	1,680	1,149	1,552.46	1,122.16	185.62	1.08	0.67	0.16
37	1,243	1,362	944	1,289.81	1,458.48	456.39	1.04	1.07	0.48
39	1,143	1,202	842	1,870.22	1,870.22	491.12	1.64	1.56	0.58
41	1,043	1,043	739	1,250.12	1,493.20	357.18	1.20	1.43	0.48
43	1,083	1,043	863	1,622.18	1,775.97	644.90	1.50	1.70	0.75

ตารางที่ ค.5 ค่า VFA และ Alkalinity ของระบบ Two-stage CSTR (ต่อ)

วันที่	Alkalinity (mg/L as $CaCO_3$)			VFA (mg/L as mg/L as CH_3COOH)			VFA/Alkalinity		
	Feed	CSTR 1	CSTR 2	Feed	CSTR 1	CSTR 2	Feed	CSTR 1	CSTR 2
44	1,124	1,043	987	1,733.80	1,798.29	135.00	1.54	1.72	0.14
47	1,164	1,043	1,111	1,845.42	1,820.61	510.96	1.59	1.75	0.46
49	1,204	1,043	1,235	1,336.14	1,257.15	413.68	1.11	1.21	0.33
54	1,184	1,154	860	826.85	1,033.57	316.40	0.70	0.90	0.37
59	1,245	1,306	1,113	1,381.60	1,590.43	210.93	1.11	1.22	0.19
64	1,235	1,797	1,346	1381.60	1754.95	126.56	1.12	0.98	0.09
69	1,377	1,194	1,255	1,936.35	2,008.07	371.24	1.41	1.68	0.30
74	1,285	1,204	1,316	1,936.35	1,767.61	624.36	1.51	1.47	0.47
79	1,103	1,336	1,468	1,936.35	295.30	371.94	1.76	0.22	0.25
84	2,186	2,186	2,571	1,034.44	783.04	119.52	0.47	0.36	0.05
89	2,368	2,247	2,611	984.99	647.04	168.97	0.42	0.29	0.06
94	2,105	2,785	2,490	984.99	395.64	160.73	0.47	0.14	0.06
99	1,903	2,348	2,591	616.02	672.85	121.47	0.32	0.29	0.05
104	2,510	2,267	2,986	587.83	950.06	134.48	0.23	0.42	0.05
108	2,075	2,186	2,146	559.63	1,258.08	125.81	0.27	0.58	0.06
115	2,115	2,308	3,077	616.02	1,197.34	858.96	0.29	0.52	0.28
120	2,126	2,328	2,834	914.77	1,524.26	895.22	0.43	0.65	0.32
125	1,660	2,247	2,814	914.77	1,524.26	895.22	0.55	0.68	0.32

ตารางที่ ค.5 ค่า VFA และ Alkalinity ของระบบ Two-stage CSTR (ต่อ)

วันที่	Alkalinity (mg/L as $CaCO_3$)			VFA (mg/L as mg/L as CH_3COOH)			VFA/Alkalinity		
	Feed	CSTR 1	CSTR 2	Feed	CSTR 1	CSTR 2	Feed	CSTR 1	CSTR 2
130	1,660	2,024	2,935	1,214	1,851	931	0.73	0.91	0.32
135	1,923	1,923	1,883	1,512.26	2,178.09	967.74	0.79	1.13	0.51
140	1,356	1,761	2,267	1,512.26	2,178.09	967.74	1.12	1.24	0.43
146	2,065	1,923	2,227	1,811	2,505	1,004	0.88	1.30	0.45
151	1,599	1,862	2,571	1,634	2,457	661	1.02	1.32	0.26
156	2,065	2,238	2,530	1,547	2,150	475	0.75	0.96	0.19
161	1,194	2,446	1,883	1,457	2,267	248	1.22	0.93	0.13
166	2,507	2,614	2,857	1,945	2,411	523	0.78	0.92	0.18
171	2,213	2,654	2,966	2,053	2,353	333	0.93	0.89	0.11
177	2,462	2,620	2,825	1,752	2,052	354	0.71	0.78	0.13
182	2,583	2,748	2,930	1,656	2,250	497	0.64	0.82	0.17
187	2,184	2,630	2,807	1,356	2,267	515	0.62	0.86	0.18
192	2,301	2,710	2,830	1,558	1,956	559	0.68	0.72	0.20
197	2,546	2,680	2,870	1,680	2,351	438	0.66	0.88	0.15
202	2,459	2,638	2,934	2,009	2,166	526	0.82	0.82	0.18
208	2,551	2,651	2,809	1,854	2,450	380	0.73	0.92	0.14
213	2,322	2,701	2,983	1,981	2,250	600	0.85	0.83	0.20
40	79.81	66.40	8.83	65,320.30	65,320.30	65,320.30	818	984	7,396

6. ค่า TKN ของระบบ Two-stage CSTR

ตารางที่ ค.6 ค่า TKN ของระบบ Two-stage CSTR

วันที่	TKN (mg/L)			COD (mg/L)			C/N ratio		
	Influent	Effluent CSTR 1	Effluent CSTR 2	Influent	Effluent CSTR 1	Effluent CSTR 2	Influent	Effluent CSTR 1	Effluent CSTR 2
45	79.81	51.98	11.78	48,327.14	48,327.14	48,327.14	606	930	4,104
50	69.91	33.97	12.43	48,327.14	48,327.14	48,327.14	691	1,423	3,888
55	68.93	25.07	13.73	70,631.97	70,631.97	70,631.97	648	2,817	5,145
60	66.22	23.88	15.02	40,000.00	40,000.00	40,000.00	604	1,675	2,662
65	51.84	20.93	11.56	43,809.52	43,809.52	43,809.52	845	2,093	3,791
70	76.15	1.64	0.33	40,000.00	40,000.00	40,000.00	525	2,383	4,041
75	52.98	18.88	11.76	50,476.19	50,476.19	50,476.19	953	2,674	4,291
80	52.28	29.29	11.93	34,285.71	34,285.71	34,285.71	656	1,170	2,875
85	17.65	5.69	17.45	39,484.78	39,484.78	39,484.78	2,237	6,944	2,263
90	66.27	47.25	17.71	55,081.97	55,081.97	55,081.97	831	1,166	3,110
95	13.73	49.41	17.91	62,086.44	62,086.44	62,086.44	4,523	1,257	3,467
100	85.95	30.21	18.89	69,090.91	69,090.91	69,090.91	804	2,287	3,657
105	42.60	51.05	18.95	47,501.73	47,501.73	47,501.73	1,115	931	2,506
110	36.78	79.20	17.70	47,693.66	47,693.66	47,693.66	1,297	602	2,694
115	85.20	15.76	15.89	47,272.73	47,272.73	47,272.73	555	2,999	2,975
120	99.65	11.64	21.08	41,952.31	41,952.31	41,952.31	421	3,606	1,990

ตารางที่ ค.6 ค่า TKN ของระบบ Two-stage CSTR (ต่อ)

วันที่	TKN (mg/L)			COD (mg/L)			C/N ratio		
	Influent	Effluent CSTR 1	Effluent CSTR 2	Influent	Effluent CSTR 1	Effluent CSTR 2	Influent	Effluent CSTR 1	Effluent CSTR 2
125	99.65	47.10	19.39	32,727.27	32,727.27	32,727.27	328	695	1,688
130	83.51	15.58	17.27	30,259.74	27,792.21	20,346.32	362	1,784	1,178
135	85.39	41.85	19.45	29,951.30	35,411.26	24,155.84	351	846	1,242
140	68.12	52.73	13.70	27,792.21	22,857.14	15,238.10	408	433	1,112
146	79.92	74.15	58.00	22,857.14	15,238.10	7,619.05	286	206	131
151	86.12	66.00	45.35	22,857.14	15,238.10	15,238.10	265	231	336
156	69.02	51.87	34.80	55,081.97	55,081.97	27,540.98	798	1,062	791
161	52.09	53.41	42.00	49,225.04	30,134.13	15,067.06	945	564	359
166	52.39	36.50	31.25	42,402.60	22,077.92	11,991.34	809	605	384
171	66.31	41.75	38.50	37,532.47	22,337.66	13,073.59	566	535	340
177	51.95	52.20	28.90	27,792.21	22,857.14	15,238.10	535	438	527
182	42.79	49.30	18.00	33,638.49	29,960.97	20,649.02	786	608	1,147
187	36.87	32.45	28.00	39,484.78	37,064.79	26,059.95	1,071	1,142	931
192	73.79	67.32	50.15	37,178.52	34,746.65	24,235.22	504	516	483
197	17.74	53.21	38.75	32,566.00	30,110.35	20,585.77	1,836	566	531
202	85.04	63.50	43.60	37,471.79	41,437.09	22,115.41	441	653	507
208	66.36	52.68	31.50	44,683.84	55,081.97	25,469.79	673	1,046	809
213	83.60	44.99	27.30	41,000.71	50,164.29	23,265.57	490	1,115	852

7. ค่า F/M Ratio ของระบบ Two-stage CSTR

ตารางที่ ค.7 ค่า F/M ratio ของระบบ Two-stage CSTR

วันที่	MLVSS (mg/L)	TVS_{fed} (mg/L)	COD_{fed} (mg/L)	F/M ratio (d^{-1})	
				COD/(MLVSS*HRT)	TVS/(MLVSS*HRT)
1	392	6,980	25,547	2.71	17.79
2	231	2,050	25,547	4.61	8.88
3	255	1,500	25,547	4.17	5.88
4	364	6,795	25,547	2.93	18.69
5	514	7,140	25,547	2.07	13.90
6	593	4,650	25,547	1.80	7.85
7	798	5,615	22,901	1.20	7.04
8	525	7,780	22,901	1.82	14.83
9	592	9,375	22,901	1.61	15.83
10	614	10,490	14,286	0.97	17.08
12	767	8,020	14,286	0.78	10.46
14	683	3,060	14,286	0.87	4.48
15	686	3,225	14,286	0.87	4.70
16	630	4,465	14,286	0.94	7.09
17	862	5,090	21,429	1.04	5.90
32	1,472	13,220	14,981	0.42	8.98
34	19,852	17,285	14,981	0.03	0.87
49	14,638	5,760	33,457	0.10	0.39
55	16,164	21,040	26,022	0.07	1.30
57	17,904	19,621	19,048	0.04	1.10
64	10,612	20,445	30,476	0.12	1.93
65	26,084	20,445	22,857	0.04	0.78
99	31,896	12,020	10,909	0.01	0.38
152	61,588	8,694	15,238	0.01	0.14
156	26,628	9,072	15,238	0.02	0.34
159	20,852	9,450	15,238	0.03	0.45
176	13,725	12,295	27,792	0.08	0.90
177	14,484	9,295	33,638	0.10	0.64
178	15,030	6,570	39,485	0.11	0.44

ตารางที่ ค.7 ค่า F/M ratio ของระบบ Two-stage CSTR (ต่อ)

วันที่	MLVSS (mg/L)	TVS_{fed} (mg/L)	COD_{fed} (mg/L)	F/M ratio (d^{-1})	
				COD/(MLVSS*HRT)	TVS/(MLVSS*HRT)
179	13,662	9,450	37,179	0.11	0.69
180	14,815	14,920	32,566	0.09	1.01
181	15,944	7,655	37,472	0.10	0.48
182	12,586	15,840	44,684	0.15	1.26
183	16,242	12,020	41,001	0.11	0.74

8. ค่า Yield biogas ของระบบ Two-stage CSTR

ตารางที่ ค.8 ค่า Yield biogas ของระบบ Two-stage CSTR

วันที่	Yield biogas		วันที่	Yield biogas	
	ml biogas/L-d	ml biogas/g $TVS_{removed}$-d		ml biogas/L-d	ml biogas/g $TVS_{removed}$-d
37	2.67	0.12	93	21.33	2.30
40	24.00	1.38	96	29.33	2.75
43	8.00	0.59	99	29.33	2.44
46	8.00	0.83	102	61.33	5.10
49	2.67	0.46	105	50.67	4.22
52	2.67	0.13	108	101.33	8.43
55	5.33	0.25	110	114.67	7.34
58	21.33	1.09	113	93.33	6.26
61	48.00	2.64	115	96.00	6.41
64	82.67	4.04	118	104.00	6.09
67	74.67	4.86	122	58.67	3.23
71	98.67	6.29	125	61.33	3.19
73	82.67	5.17	127	58.67	4.10
77	64.00	6.15	130	0.04	4.51
79	106.67	7.13	133	0.02	4.07
82	69.33	7.46	136	0.02	3.23
85	53.33	5.23	139	0.04	4.46
87	29.33	3.01	140	0.02	2.66
90	26.67	2.80	142	0.01	1.33

ตารางที่ ค.8 ค่า Yield biogas ของระบบ Two-stage CSTR (ต่อ)

วันที่	Yield biogas		วันที่	Yield biogas	
	ml biogas/L-d	ml biogas/g $TVS_{removed}$-d		ml biogas/L-d	ml biogas/g $TVS_{removed}$-d
145	0.01	1.00	180	0.02	2.28
148	0.02	1.90	183	0.01	1.78
151	0.02	2.22	186	0.01	2.15
152	0.01	1.62	189	0.02	2.01
156	0.02	1.95	192	0.02	1.87
159	0.02	1.87	195	0.02	1.23
162	0.03	1.94	198	0.02	1.18
165	0.01	2.02	201	0.01	1.84
168	0.02	2.83	204	0.02	1.11
171	0.01	1.84	207	0.02	1.11
174	0.02	1.44	210	0.02	1.66
177	0.02	2.48	213	0.02	1.47

ภาคผนวก ง

ผลของสมดุลมวลในระบบ Two-stage CSTR

1. สมดุลมวลคาร์บอนของระบบ Two-stage CSTR

ตารางที่ ง.1 ปริมาณคาร์บอนที่จุดต่าง ๆ ของระบบ Two-stage CSTR

<table>
<tr><th colspan="2" rowspan="2">ตัวอย่าง</th><th rowspan="2">ซ้ำ</th><th rowspan="2">Flowrate (L/day)</th><th colspan="3">สัดส่วน</th><th colspan="3">TS (mg/L)</th><th colspan="2">Carbon</th><th colspan="3">Carbon (g C/day)</th></tr>
<tr><th>(ml)</th><th>(%)</th><th>เฉลี่ย</th><th>TS (mg/L)</th><th>เฉลี่ย</th><th>รวม</th><th>% C in dry sludge</th><th>(mg C/L)</th><th>(g C/day)</th><th>เฉลี่ย</th><th>รวม</th></tr>
<tr><td rowspan="10">Feed</td><td rowspan="5">Feed (Liquid)</td><td>1</td><td rowspan="10">1.64</td><td>249</td><td>53.66</td><td rowspan="5">60.91</td><td>2,140</td><td rowspan="5">2,026</td><td rowspan="10">22,773</td><td>-</td><td>267.90</td><td>0.24</td><td rowspan="5">0.25</td><td rowspan="10">7.36</td></tr>
<tr><td>2</td><td>163</td><td>48.08</td><td>1,995</td><td>-</td><td>271.80</td><td>0.21</td></tr>
<tr><td>3</td><td>235</td><td>70.15</td><td>1,920</td><td>-</td><td>235.60</td><td>0.27</td></tr>
<tr><td>4</td><td>313</td><td>70.65</td><td>1,985</td><td>-</td><td>258.20</td><td>0.30</td></tr>
<tr><td>5</td><td>212</td><td>61.99</td><td>2,090</td><td>-</td><td>247.90</td><td>0.25</td></tr>
<tr><td rowspan="5">Feed (Solid)</td><td>1</td><td>215</td><td>46.34</td><td rowspan="5">39.09</td><td>78,873</td><td rowspan="5">55,097</td><td>19.00</td><td>-</td><td>11.39</td><td rowspan="5">7.10</td></tr>
<tr><td>2</td><td>176</td><td>51.92</td><td>63,799</td><td>19.70</td><td>-</td><td>10.70</td></tr>
<tr><td>3</td><td>100</td><td>29.85</td><td>25,126</td><td>18.47</td><td>-</td><td>2.27</td></tr>
<tr><td>4</td><td>130</td><td>29.35</td><td>46,016</td><td>18.37</td><td>-</td><td>4.07</td></tr>
<tr><td>5</td><td>130</td><td>38.01</td><td>61,670</td><td>18.45</td><td>-</td><td>7.09</td></tr>
</table>

ตารางที่ ง.1 ปริมาณคาร์บอนที่จุดต่าง ๆ ของระบบ Two-stage CSTR (ต่อ)

ตัวอย่าง		ซ้ำ	Flowrate (L/day)	สัดส่วน			TS (mg/L)			Carbon		Carbon (g C/day)		
				(ml)	(%)	เฉลี่ย	TS (mg/L)	เฉลี่ย	รวม	% C in dry sludge	(mg C/L)	(g C/day)	เฉลี่ย	รวม
CSTR 1	CSTR 1 (Liquid)	1	1.64	409	69.91	72.41	2,005	1,909	16,565	-	289.80	0.33	0.35	4.97
		2		357	70.41		1,975			-	293.60	0.34		
		3		475	81.76		1,825			-	294.60	0.39		
		4		357	71.83		1,760			-	300.00	0.35		
		5		475	68.15		1,980			-	285.10	0.32		
	CSTR 1 (Solid)	1		176	30.09	27.59	64,622	55,036		19.73	-	6.29	4.62	
		2		150	29.59		40,372			18.81	-	3.68		
		3		106	18.24		49,249			18.44	-	2.72		
		4		140	28.17		59,883			18.31	-	5.06		
		5		222	31.85		61,053			16.72	-	5.33		
Effluent CSTR 1	Effluent CSTR 1 (Liquid)	1	1.64	337	77.65	66.21	1,755	1,810	21,145	-	283.60	0.36	0.33	7.56
		2		146	31.33		2,105			-	406.50	0.21		
		3		409	69.91		1,690			-	294.40	0.34		
		4		357	70.41		1,840			-	295.80	0.34		
		5		475	81.76		1,660			-	287.80	0.39		

ตารางที่ ง.1 ปริมาณคาร์บอนที่จุดต่าง ๆ ของระบบ Two-stage CSTR (ต่อ)

ตัวอย่าง		ซ้ำ	Flowrate (L/day)	สัดส่วน			TS (mg/L)			Carbon		Carbon (g C/day)		
				(ml)	(%)	เฉลี่ย	TS (mg/L)	เฉลี่ย	รวม	% C in dry sludge	(mg C/L)	(g C/day)	เฉลี่ย	รวม
Effluent CSTR 1 (ต่อ)	Effluent CSTR 1 (Solid)	1		97	22.35	33.79	41,878	59,037		18.63	-	2.86	7.24	7.56
		2		320	68.67		99,062			18.50	-	20.63		
		3		176	30.09		64,622			19.73	-	6.29		
		4		150	29.59		40,372			18.81	-	3.68		
		5		106	18.24		49,249			18.44	-	2.72		
CSTR 2	CSTR 2 (Liquid)	1	0.82	148	59.68	39.73	1,755	1,640	37,882	-	300.80	0.15	0.10	4.91
		2		108	41.86		1,810			-	308.70	0.11		
		3		119	43.43		1,915			-	310.10	0.11		
		4		116	42.03		1,755			-	302.60	0.10		
		5		29	11.65		965			-	291.40	0.03		
	CSTR 2 (Solid)	1		100	40.32	60.27	71,241	61,772		16.77	-	3.95	4.81	
		2		150	58.14		57,979			17.59	-	4.86		
		3		155	56.57		52,332			15.47	-	3.76		
		4		160	57.97		68,902			15.39	-	5.04		
		5		220	88.35		58,405			15.29	-	6.47		

ตารางที่ ง.1 ปริมาณคาร์บอนที่จุดต่าง ๆ ของระบบ Two-stage CSTR (ต่อ)

ตัวอย่าง		ซ้ำ	Flowrate (L/day)	สัดส่วน			TS (mg/L)			Carbon		Carbon (g C/day)		
				(ml)	(%)	เฉลี่ย	TS (mg/L)	เฉลี่ย	รวม	% C in dry sludge	(mg C/L)	(g C/day)	เฉลี่ย	รวม
Effluent CSTR 2	Effluent CSTR 2 (Liquid)	1	0.72	-	100	100	1,870	1,996	1,996	-	279.00	0.20	0.21	0.21
		2		-	100		1,990			-	291.50	0.21		
		3		-	100		2,175			-	294.90	0.21		
		4		-	100		1,985			-	281.10	0.20		
		5		-	100		1,960			-	302.40	0.22		
Excess Sludge CSTR 2		1	0.1	-	100	100	-	37,882	37,882	-	-	-	0.60	0.60
		2		-	100		-			-	-	-		
		3		-	100		-			-	-	-		
		4		-	100		-			-	-	-		
		5		-	100		-			-	-	-		
Biogas		-	1.66	-	-	-	-	-	-	-	-	-	0.89	0.89

2. สมดุลมวลไนโตรเจนของระบบ Two-stage CSTR

ตารางที่ ง.2 ปริมาณไนโตรเจนที่จุดต่าง ๆ ของระบบ Two-stage CSTR

ตัวอย่าง		ซ้ำ	Flowrate (L/day)	สัดส่วน			TS (mg/L)			Nitrogen		Nitrogen (g N/day)		
				(ml)	(%)	เฉลี่ย	TS (mg/L)	เฉลี่ย	รวม	% N in dry sludge	(mg N/L)	(g N/day)	เฉลี่ย	รวม
Feed	Feed (Liquid)	1	1.64	249	53.66	60.91	2,140	2,026	22,773	-	32.64	0.03	0.02880	0.59
		2		163	48.08		1,995			-	53.42	0.04		
		3		235	70.15		1,920			-	17.55	0.02		
		4		313	70.65		1,985			-	20.13	0.02		
		5		212	61.99		2,090			-	29.17	0.03		
	Feed (Solid)	1		215	46.34	39.09	78,873	55,097		1.54	-	0.92	0.57	
		2		176	51.92		63,799			1.51	-	0.82		
		3		100	29.85		25,126			1.48	-	0.18		
		4		130	29.35		46,016			1.50	-	0.33		
		5		130	38.01		61,670			1.49	-	0.57		

ตารางที่ ง.2 ปริมาณไนโตรเจนที่จุดต่าง ๆ ของระบบ Two-stage CSTR (ต่อ)

ตัวอย่าง		ซ้ำ	Flowrate (L/day)	สัดส่วน			TS (mg/L)			Nitrogen		Nitrogen (g N/day)		
				(ml)	(%)	เฉลี่ย	TS (mg/L)	เฉลี่ย	รวม	% N in dry sludge	(mg N/L)	(g N/day)	เฉลี่ย	รวม
CSTR 1	CSTR 1 (Liquid)	1	1.64	409	69.91	72.41	2,005	1,909	16,565	-	38.60	0.04	0.03982	0.42
		2		357	70.41		1,975			-	41.00	0.05		
		3		475	81.76		1,825			-	27.15	0.04		
		4		357	71.83		1,760			-	24.85	0.03		
		5		475	68.15		1,980			-	37.41	0.04		
	CSTR 1 (Solid)	1		176	30.09	27.59	64,622	55,036		1.47	-	0.47	0.38	
		2		150	29.59		40,372			1.49	-	0.29		
		3		106	18.24		49,249			1.54	-	0.23		
		4		140	28.17		59,883			1.51	-	0.42		
		5		222	31.85		61,053			1.48	-	0.47		
Effluent CSTR 1	Effluent CSTR 1 (Liquid)	1	1.64	337	77.65	66.21	1,755	1,810	21,145	-	45.12	0.06	0.04255	0.61
		2		146	31.33		2,105			-	87.56	0.04		
		3		409	69.91		1,690			-	27.32	0.03		
		4		357	70.41		1,840			-	24.00	0.03		
		5		475	81.76		1,660			-	38.25	0.05		

ตารางที่ ง.2 ปริมาณไนโตรเจนที่จุดต่าง ๆ ของระบบ Two-stage CSTR (ต่อ)

ตัวอย่าง		ซ้ำ	Flowrate (L/day)	สัดส่วน			TS (mg/L)			Nitrogen		Nitrogen (g N/day)		
				(ml)	(%)	เฉลี่ย	TS (mg/L)	เฉลี่ย	รวม	% N in dry sludge	(mg N/L)	(g N/day)	เฉลี่ย	รวม
Effluent CSTR 1 (ต่อ)	Effluent CSTR 1 (Solid)	1		97	22.35	33.79	41,878	59,037		1.49	-	0.23	0.56	0.61
		2		320	68.67		99,062			1.46	-	1.63		
		3		176	30.09		64,622			1.40	-	0.45		
		4		150	29.59		40,372			1.48	-	0.29		
		5		106	18.24		49,249			1.49	-	0.22		
CSTR 2	CSTR 2 (Liquid)	1	0.82	148	59.68	39.73	1,755	1,640	37,882	-	108.70	0.05	0.03	0.43
		2		108	41.86		1,810			-	100.10	0.03		
		3		119	43.43		1,915			-	99.78	0.04		
		4		116	42.03		1,755			-	104.10	0.04		
		5		29	11.65		965			-	82.31	0.01		
	CSTR 2 (Solid)	1		100	40.32	60.27	71,241	61,772		1.29	-	0.30	0.39	
		2		150	58.14		57,979			1.30	-	0.36		
		3		155	56.57		52,332			1.31	-	0.32		
		4		160	57.97		68,902			1.28	-	0.42		
		5		220	88.35		58,405			1.32	-	0.56		

ตารางที่ ง.2 ปริมาณไนโตรเจนที่จุดต่าง ๆ ของระบบ Two-stage CSTR (ต่อ)

ตัวอย่าง		ซ้ำ	Flowrate (L/day)	สัดส่วน			TS (mg/L)			Nitrogen		Nitrogen (g N/day)		
				(ml)	(%)	เฉลี่ย	TS (mg/L)	เฉลี่ย	รวม	% N in dry sludge	(mg N/L)	(g N/day)	เฉลี่ย	รวม
Effluent CSTR 2	Effluent CSTR 2 (Liquid)	1	0.72	-	100	100	1,870	1,996	1,996	-	123.30	0.09	0.08932	0.08932
		2		-	100		1,990			-	120.50	0.09		
		3		-	100		2,175			-	140.10	0.10		
		4		-	100		1,985			-	121.10	0.09		
		5		-	100		1,960			-	115.30	0.08		
Excess Sludge CSTR 2		1	0.1	-	100	100	-	37,882	37,882	-	-	-	0.05193	0.05193
		2		-	100		-			-	-	-		
		3		-	100		-			-	-	-		
		4		-	100		-			-	-	-		
		5		-	100		-			-	-	-		

3. สมดุลมวลฟอสฟอรัสของระบบ Two-stage CSTR

ตารางที่ ง.3 ปริมาณฟอสฟอรัสที่จุดต่าง ๆ ของระบบ Two-stage CSTR

ตัวอย่าง	ซ้ำ	Flowrate (L/day)	TS (mg/L)		Phosphorus (mg P/L)		Phosphorus (g P/day)
			TS (mg/L)	เฉลี่ย	P (mg P/L)	เฉลี่ย	
	1		3,640		32.92		
	2		4,770		44.46		
Feed	3	1.64	8,190	7,358	56.00	48.45	0.079
	4		10,100		54.96		
	5		10,090		53.92		
	1		4,530		58.08		
	2		7,480		55.58		
CSTR 1	3	1.64	5,220	6,774	53.08	62.58	0.103
	4		7,520		66.42		
	5		9,120		79.75		
	1		4,530		58.08		
	2		7,480		55.58		
Effluent CSTR 1	3	1.64	5,220	6,774	53.08	62.58	0.103
	4		7,520		66.42		
	5		9,120		79.75		

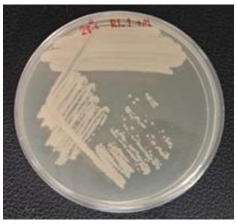
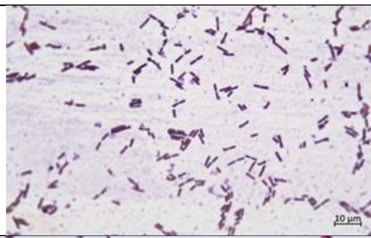
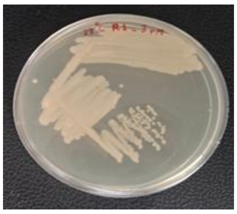
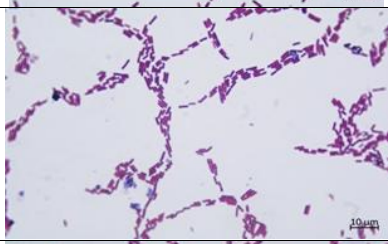
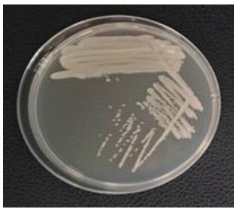
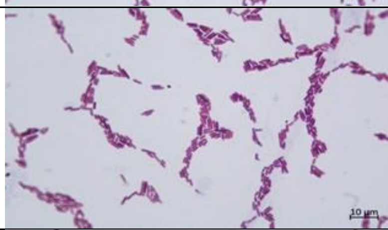
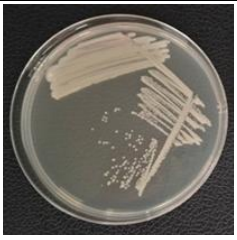
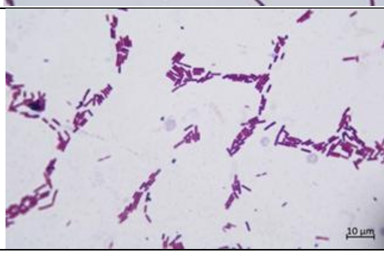
ตารางที่ ง.3 ปริมาณฟอสฟอรัสที่จุดต่าง ๆ ของระบบ Two-stage CSTR (ต่อ)

ตัวอย่าง	ซ้ำ	Flowrate (L/day)	TS (mg/L)		Phosphorus (mg P/L)		Phosphorus (g P/day)
			TS (mg/L)	เฉลี่ย	P (mg P/L)	เฉลี่ย	
CSTR 2	1	0.82	42,970	35,018	60.58	59.50	0.049
	2		25,120		57.67		
	3		30,800		54.75		
	4		42,690		59.75		
	5		33,510		64.75		
Effluent CSTR 2	1	0.72	1,930	1,762	64.75	69.50	0.050
	2		1,820		67.88		
	3		1,670		71.00		
	4		1,720		71.63		
	5		1,670		72.25		
Excess Sludge CSTR 2	1	0.1	-	35,018	60.58	59.50	0.0060
	2		-		57.67		
	3		-		54.75		
	4		-		59.75		
	5		-		64.75		

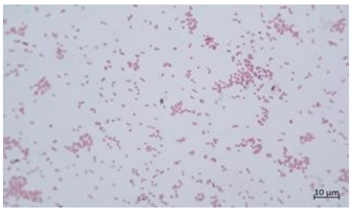
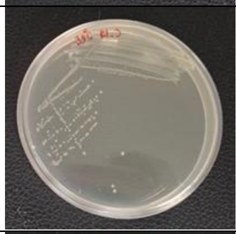
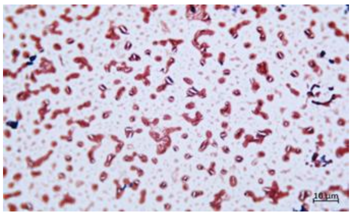
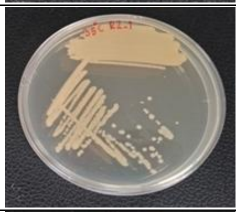
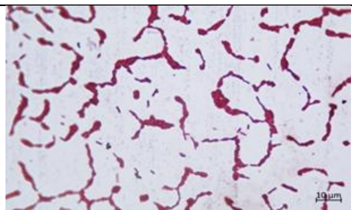
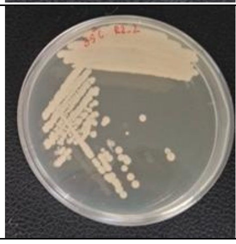
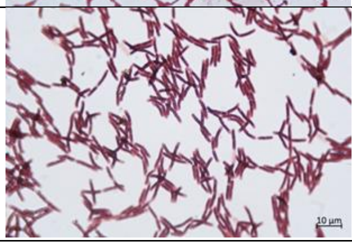
ภาคผนวก จ

ผลการวิเคราะห์ชุมชนทางจุลินทรีย์ของ
ระบบ Two-stage CSTR

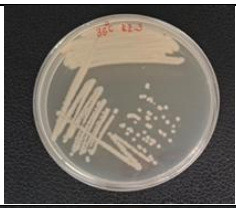
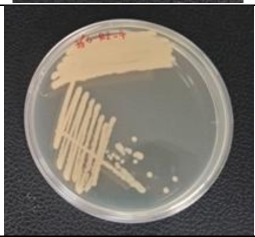
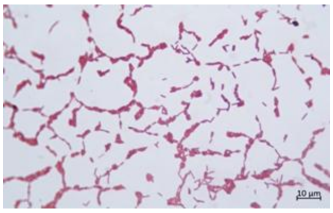
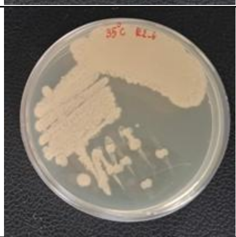
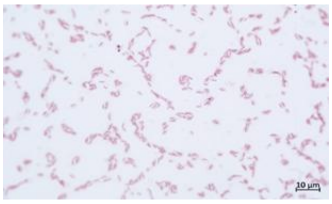
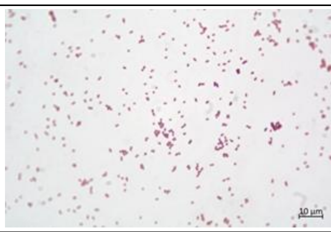
ตารางที่ จ.1 ลักษณะโคโลนีของเชื้อจุลินทรีย์บนอาหารเลี้ยงเชื้อและลักษณะภายใต้กล้องจุลทรรศน์

ตัวอย่าง	รูปภาพ	รูปภาพใต้กล้องจุลทรรศน์หลังย้อมแกรม
28°C CSTR 1_1+M		
28°C CSTR 1_2+M		
28°C CSTR 1_3+M		
28°C CSTR 2_1+M		
28°C CSTR 2_2+M		
28°C CSTR 2_3+M		

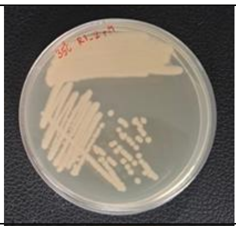
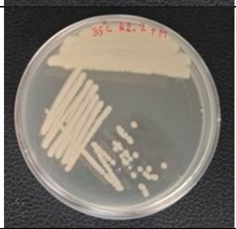
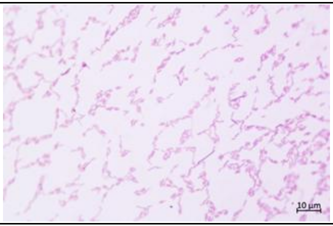
ตารางที่ จ.1 ลักษณะโคโลนีของเชื้อจุลินทรีย์บนอาหารเลี้ยงเชื้อและลักษณะภายใต้กล้องจุลทรรศน์ (ต่อ)

ตัวอย่าง	รูปภาพ	รูปภาพใต้กล้องจุลทรรศน์หลังย้อมแกรม
35°C CSTR 1_1		
35°C CSTR 1_2		
35°C CSTR 1_3		
35°C CSTR 1_4		
35°C CSTR 2_1		
35°C CSTR 2_2		

ตารางที่ จ.1 ลักษณะโคโลนีของเชื้อจุลินทรีย์บนอาหารเลี้ยงเชื้อและลักษณะภายใต้กล้องจุลทรรศน์ (ต่อ)

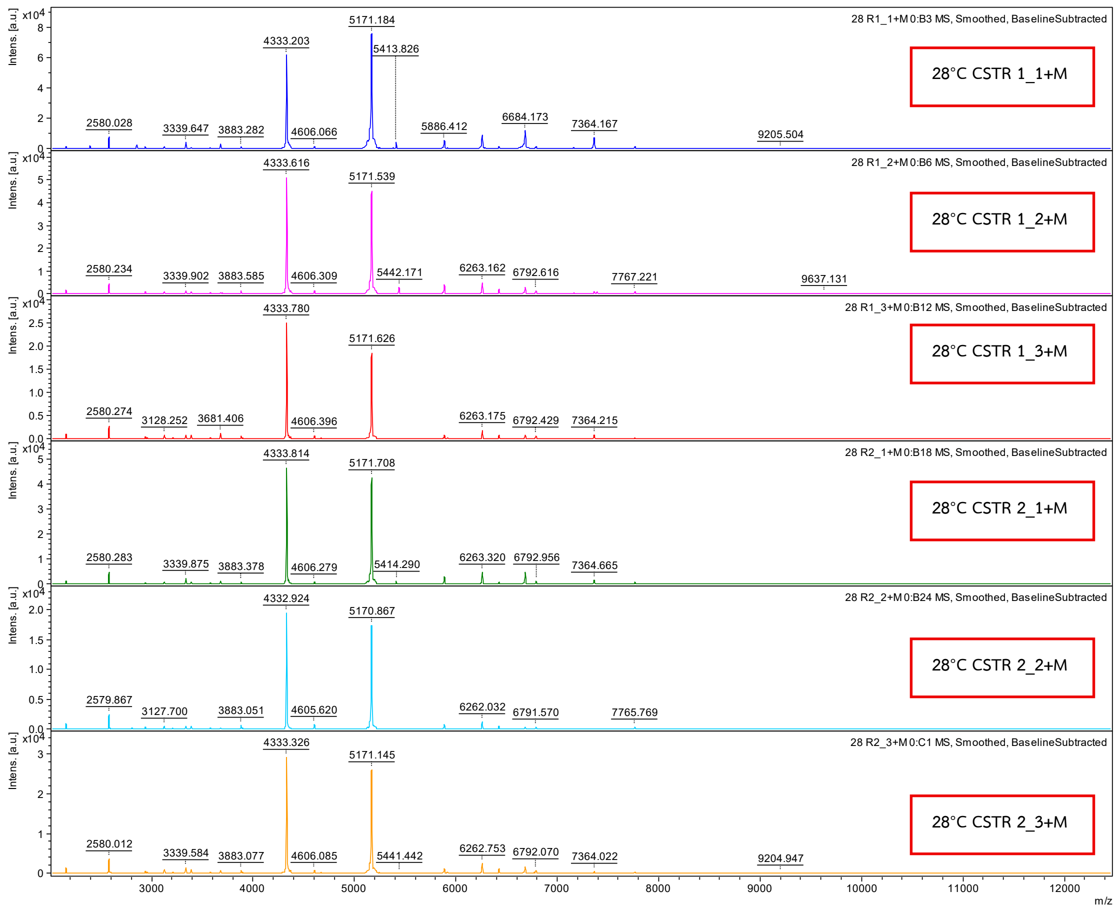
ตัวอย่าง	รูปภาพ	รูปภาพใต้กล้องจุลทรรศน์หลังย้อมแกรม
35°C CSTR 2_3		
35°C CSTR 2_4		
35°C CSTR 2_5		
35°C CSTR 2_6		
35°C CSTR 2_7		
35°C CSTR 1_1+M		

ตารางที่ จ.1 ลักษณะโคโลนีของเชื้อจุลินทรีย์บนอาหารเลี้ยงเชื้อและลักษณะภายใต้กล้องจุลทรรศน์ (ต่อ)

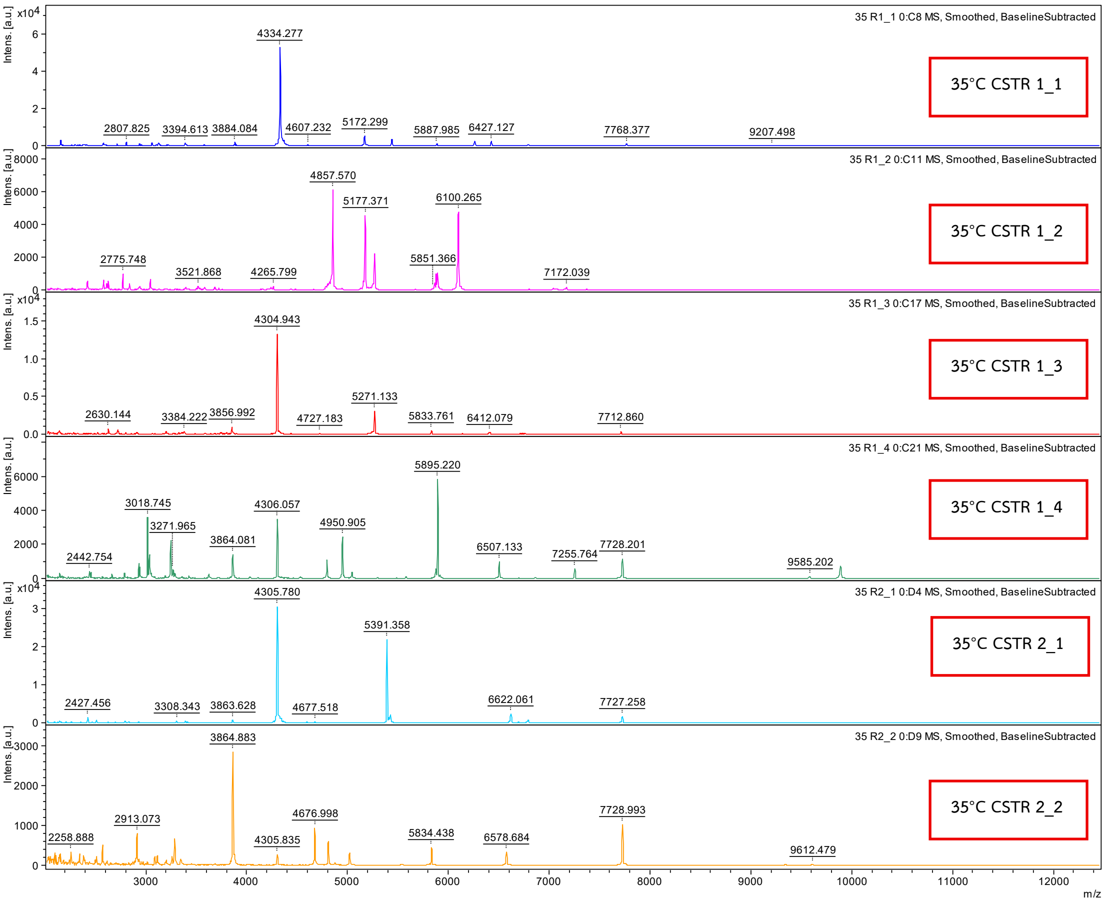
ตัวอย่าง	รูปภาพ	รูปภาพใต้กล้องจุลทรรศน์หลังย้อมแกรม
35°C CSTR 1_2+M		
35°C CSTR 1_3+M		
35°C CSTR 2_1+M		
35°C CSTR 2_2+M		
35°C CSTR 2_3+M		
35°C CSTR 2_4+M		

ตารางที่ จ.2 ผลการระบุสายพันธุ์จุลินทรีย์

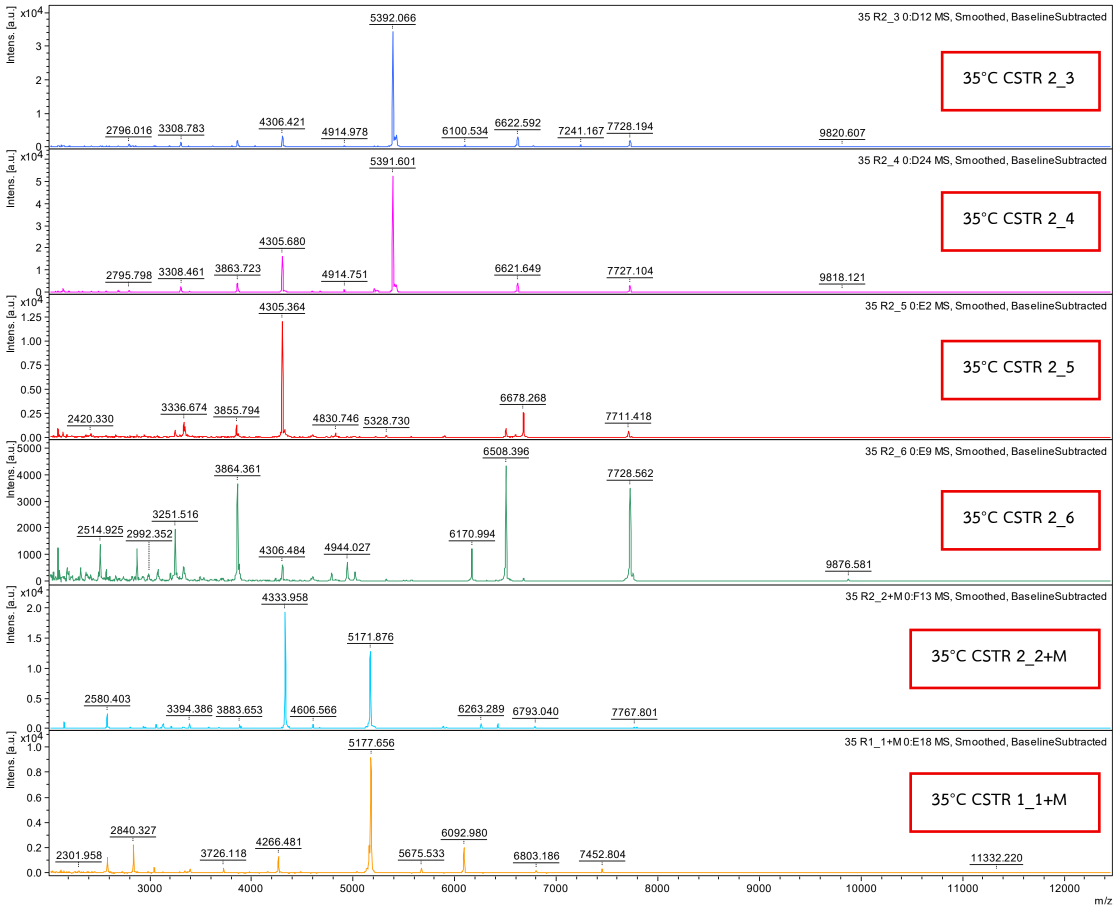
ตัวอย่าง	ผลการระบุสายพันธุ์	คะแนน	หมายเหตุ
28°C CSTR 1_1+M	*Bacillus cereus*	2.189	*Bacillus cereus* DSM 31T DSM
28°C CSTR 1_2+M	*Bacillus cereus*	2.303	*Bacillus cereus* DSM 31T DSM
28°C CSTR 1_3+M	*Bacillus cereus*	2.238	*Bacillus cereus* DSM 31T DSM
28°C CSTR 2_1+M	*Bacillus cereus*	2.201	*Bacillus cereus* DSM 31T DSM
28°C CSTR 2_2+M	*Bacillus cereus*	2.260	*Bacillus cereus* DSM 31T DSM
28°C CSTR 2_3+M	*Bacillus cereus*	2.312	*Bacillus cereus* DSM 31T DSM
35°C CSTR 1_1	*Bacillus cereus*	2.001	*Bacillus cereus* DSM 31T DSM
35°C CSTR 1_2	*Stenotrophomonas maltophilia*	1.997	*Stenotrophomonas maltophilia* LMG 980T HAM
35°C CSTR 1_3	*Bacillus flexus*	1.899	*Bacillus flexus* DSM 1320T DSM
35°C CSTR 1_4	*Bacillus licheniformis*	1.706	*Bacillus licheniformis* 992000432 LBK
35°C CSTR 2_1	*Bacillus pumilus*	1.631	*Bacillus pumilus* DSM 354 DSM
35°C CSTR 2_2	*Bacillus megaterium*	1.516	*Bacillus megaterium* DSM 32T DSM
35°C CSTR 2_3	*Bacillus pumilus*	1.757	*Bacillus pumilus* IAM 12469 PAH
35°C CSTR 2_4	*Bacillus pumilus*	1.749	*Bacillus pumilus* IAM 12050 PAH
35°C CSTR 2_5	*Bacillus subtilis*	1.886	*Bacillus subtilis* DSM 5552 DSM
35°C CSTR 2_6	*Lactobacillus plantarum*	1.475	*Lactobacillus plantarum* DSM 20205 DSM
35°C CSTR 2_7	*Bacillus licheniformis*	1.843	*Bacillus licheniformis* CS 54_1 BRB
35°C CSTR 1_1+M	*Acinetobacter schindleri*	1.715	*Acinetobacter schindleri* DSM 16038T DSM
35°C CSTR 1_2+M	*Bacillus cereus*	2.204	*Bacillus cereus* DSM 31T DSM
35°C CSTR 1_3+M	*Bacillus cereus*	2.182	*Bacillus cereus* DSM 31T DSM
35°C CSTR 2_1+M	*Bacillus subtilis*	1.739	*Bacillus subtilis* ssp subtilis DSM 5660 DSM
35°C CSTR 2_2+M	*Bacillus cereus*	2.200	*Bacillus cereus* DSM 31T DSM
35°C CSTR 2_3+M	*Bacillus megaterium*	2.232	*Bacillus megaterium* DSM 32T DSM
35°C CSTR 2_4+M	*Bacillus firmus*	2.012	*Bacillus firmus* DSM 12T DSM



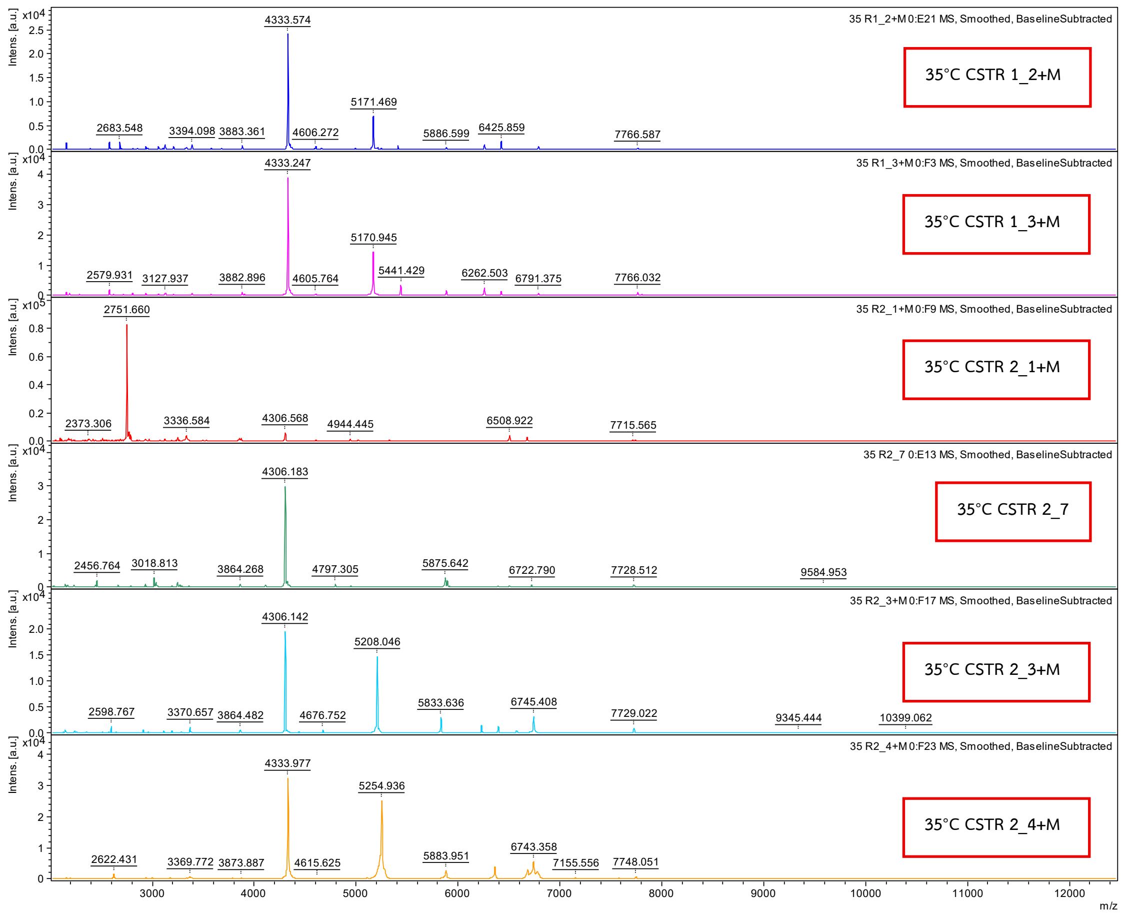
รูปที่ จ.1 Mass Spectrum แต่ละตัวอย่างที่บ่มที่อุณหภูมิ 28°C และมีการเติม Methanol 1%



รูปที่ จ.2 Mass Spectrum แต่ละตัวอย่างที่บ่มที่อุณหภูมิ 35°C



รูปที่ จ.3 Mass Spectrum แต่ละตัวอย่างที่บ่มที่อุณหภูมิ 35°C และมีการเติม Methanol 1%-1



รูปที่ จ.4 Mass Spectrum แต่ละตัวอย่างที่บ่มที่อุณหภูมิ 35°C และมีการเติม Methanol 1%-2

ภาคผนวก ฉ
ข้อมูลพื้นฐานของโรงงานกระดาษรีไซเคิลที่ศึกษา

1. ลักษณะการดำเนินกิจการของโรงงานกระดาษรีไซเคิลที่ศึกษา

โรงงานกระดาษรีไซเคิลที่ศึกษา เป็นหนึ่งในผู้ผลิตกระดาษและบรรจุภัณฑ์ครบวงจรรายใหญ่ของประเทศไทย ครองส่วนแบ่งตลาดภายในประเทศกว่า 30% และส่งออกกว่า 20% ของกำลังการผลิตไปยังประเทศในเอเชียตะวันออกเฉียงใต้ โดยมีกำลังการผลิตกระดาษ 2,500 ตันต่อวันจากโรงงาน 7 สาขา ผลิตภัณฑ์หลัก ได้แก่ กระดาษคราฟท์ กระดาษผิวหน้า กระดาษลอนลูกฟูก แผ่นกระดานลูกฟูก กล่องกระดาษลูกฟูก ถุงกระดาษคราฟท์ และกระดาษกาวชนิดต่าง ๆ ซึ่งรองรับทั้งอุตสาหกรรมก่อสร้าง อาหารสัตว์ พลาสติก เคมีภัณฑ์ และสินค้าอุปโภคบริโภค นอกจากนี้ โรงงานยังมุ่งเน้นการพัฒนาอย่างยั่งยืนด้วยการใช้เส้นใยรีไซเคิลเป็นหลัก เพื่อลดการใช้เยื่อไม้บริสุทธิ์ควบคู่กับการควบคุมคุณภาพและระบบบำบัดน้ำเสียที่มีประสิทธิภาพสูงกว่ามาตรฐานทางกฎหมาย เพื่อป้องกันผลกระทบต่อสิ่งแวดล้อมในท้องถิ่น

2. ข้อมูลพื้นฐานของโรงงานกระดาษรีไซเคิลที่ศึกษา

การสำรวจหน่วยการผลิตในแผนกต่าง ๆ ในโรงงาน ได้แก่ กระบวนการผลิตกระดาษ ระบบบำบัดน้ำเสีย ระบบผลิตก๊าซชีวภาพ ระบบการจัดการกากตะกอนส่วนเกิน และโรงจักรไฟฟ้า มีรายละเอียดดังนี้

2.1 กระบวนการผลิตกระดาษรีไซเคิล

โรงงานนี้มีโรงผลิตกระดาษจำนวน 5 โรง โดยมีขั้นตอนการผลิตหลักที่เหมือนกัน คือ ขั้นตอนการเตรียมเยื่อ (Stock Preparation) และขั้นตอนการทำกระดาษ (Paper Machine) วัตถุดิบที่ใช้ ได้แก่ กระดาษรีไซเคิล น้ำที่ผ่านการบำบัดและนำกลับมาใช้ (Reuse Water) เยื่อจากกากตะกอนที่ผ่าน Belt Press และสารเคมีปรับปรุงคุณภาพ เช่น Filler ($CaCO_3$, Clay, TiO_2) เพื่อเพิ่มความหนาแน่นและความสว่างของกระดาษ, Retention Aid เพื่อช่วยให้เยื่อและสารเติมแต่งคงตัว, Sizing Agent และ Surface Sizing เพื่อเพิ่มความต้านทานการซึมน้ำ, Wet-end Strength Agent และ Sizing-press Starch เพื่อเพิ่มความแข็งแรงและความเรียบของผิว, รวมถึงสารช่วยอื่น ๆ เช่น Optical Brightening Agent, Dye และ Biocide

ขั้นตอนการเตรียมเยื่อประกอบด้วย การตีเยื่อผสมกับน้ำและกากตะกอน, การทำความสะอาดด้วยเครื่องปั่นเหวี่ยง, การบดเยื่อและแยกเส้นใย, การต้มเยื่อด้วยไอน้ำและสารเคมีที่เหมาะสม ตลอดจนการกรองเยื่อเพื่อลดสิ่งปนเปื้อนก่อนเข้าสู่การผลิต ส่วนขั้นตอนการทำกระดาษเริ่มจากการแยกน้ำออกที่ Wire Part ตามด้วยการกดรีด (Press Section) การอบแห้ง การฉาบแป้งด้วย Sizing-press การอบซ้ำ การขัดมัน และการม้วนเก็บพร้อมตัดแบ่งตามขนาด

ผลิตภัณฑ์ที่ได้ ได้แก่ กระดาษคราฟท์ กระดาษลอนลูกฟูก กล่องและถุงกระดาษชนิดต่าง ๆ รวมถึงกระดาษกาวและกระดาษพิเศษ ขยะจากกระบวนการผลิตส่วนใหญ่คือสิ่งปนเปื้อนจากการแยกเยื่อ เช่น เศษหิน พลาสติก หรือโลหะ ซึ่งนำไปฝังกลบ ขณะที่น้ำเสียเกิดขึ้นหลักจากกระบวนการแยกน้ำออกในช่วงต้นของการผลิต

2.2 ระบบบำบัดน้ำเสียและระบบผลิตก๊าซชีวภาพ

น้ำเสียที่เข้าสู่ระบบบำบัดมาจาก 3 แหล่งหลัก ได้แก่ กระบวนการผลิตกระดาษรีไซเคิล (โรงผลิต 1–5) น้ำจากบ่อป่าต้นธูปฤๅษี และกากตะกอนก้นถังน้ำทิ้ง ระบบบำบัด เริ่มต้นด้วยการแยกของแข็งแขวนลอยผ่าน Curve Screen และ Dissolved Air Flotation (DAF) ก่อนเข้าสู่ถังตกตะกอนขั้นต้น (Primary Sedimentation Tank) เพื่อลดของแข็ง จากนั้นน้ำใสจะเข้าสู่ระบบผลิตก๊าซชีวภาพ ขณะที่ตะกอนถูกกดรีดด้วย Belt Filter Press เพื่อนำเยื่อกลับมาใช้

ระบบผลิตก๊าซชีวภาพประกอบด้วยการปรับสภาพน้ำทิ้ง โดยเติมสารเคมี (NaOH, H_3PO_4 และ Urea) เพื่อควบคุมสมดุลจุลินทรีย์ จากนั้นน้ำเสียเข้าสู่ถังปฏิกิริยา Internal Circulation (IC) ซึ่งมีกระบวนการหมุนเวียนภายในเพื่อผลิตก๊าซชีวภาพ ก๊าซที่ได้จะผ่านการกำจัด H_2S ด้วย Gas Scrubber, Bio-reactor และ Sulfur Settler ก่อนเก็บไว้ใน Gas Buffer และส่งไปยัง Boiler เพื่อผลิตไอน้ำ (Steam) ใช้ในกระบวนการผลิตกระดาษรีไซเคิล หากมีปริมาณก๊าซส่วนเกินจะถูกระบายทิ้งโดย Biogas Flare

ด้านขั้นตอนการบำบัดน้ำเสีย น้ำจากระบบผลิตก๊าซชีวภาพเข้าสู่ถังเติมอากาศ (Aeration Tank) และถังตกตะกอนทางชีวภาพ (Secondary Sedimentation Tank) เพื่อลดค่า COD และ BOD โดยมีการเวียนตะกอนกลับเพื่อรักษาความเข้มข้นจุลินทรีย์ ส่วนน้ำใสถูกส่งไปเก็บในบ่อเก็บน้ำเพื่อนำกลับมาใช้ในกระบวนการผลิต ส่วนของเสียที่เหลือ ได้แก่ น้ำทิ้งที่ผ่านการบำบัด กากตะกอนส่วนเกิน และตะกอนซัลเฟอร์จากกระบวนการกำจัด H_2S ซึ่งปัจจุบันยังไม่มีการจัดการขั้นสุดท้าย

2.3 ระบบการจัดการกากตะกอนส่วนเกิน

กากตะกอนส่วนเกินที่เข้าสู่ระบบประกอบด้วย กากตะกอนปฐมภูมิ (Primary Sludge) จากถังตกตะกอนขั้นต้น และกากตะกอนทุติยภูมิ (Secondary Sludge) จากถังตกตะกอนทางชีวภาพของระบบ Activated Sludge (AS) โดยกากตะกอนทั้งหมดจะถูกรวบรวมในถังเก็บ Sludge ก่อนเข้าสู่กระบวนการบำบัด

ขั้นตอนการจัดการเริ่มจากการทำข้นตะกอน โดยเติม Polymer ประจุบวกเพื่อรวมตัวเป็น Floc จากนั้นทำการแยกน้ำ และรีดน้ำเพิ่มเติมด้วย Belt Filter Press น้ำที่แยกออก

บางส่วนเวียนกลับไปใช้ในถังเติมอากาศ หรือนำไปปล่อยที่บ่อป่าต้นธูปฤๅษี ทั้งนี้การล้างอุปกรณ์ด้วยน้ำทิ้งที่ผ่านการบำบัดยังทำให้เกิดน้ำเสียเพิ่มขึ้น กากตะกอนที่ผ่านการรีดน้ำจะถูกเก็บไว้ใน Hopper เพื่อลดปริมาตรและน้ำหนัก ก่อนรอบริษัทภายนอกนำไปกำจัด

ของเสียที่ได้จากระบบ ได้แก่ กากตะกอนแห้งและน้ำเสียจากกระบวนการแยกน้ำ ปัจจุบันกากตะกอนที่ผ่านการบำบัดส่วนใหญ่จะถูกรวบรวมส่งให้บริษัทภายนอกกำจัดต่อ ขณะเดียวกันยังมีการทดลองนำไปใช้ประโยชน์ในการผลิตปุ๋ย เพื่อลดปริมาณการกำจัดขั้นสุดท้าย

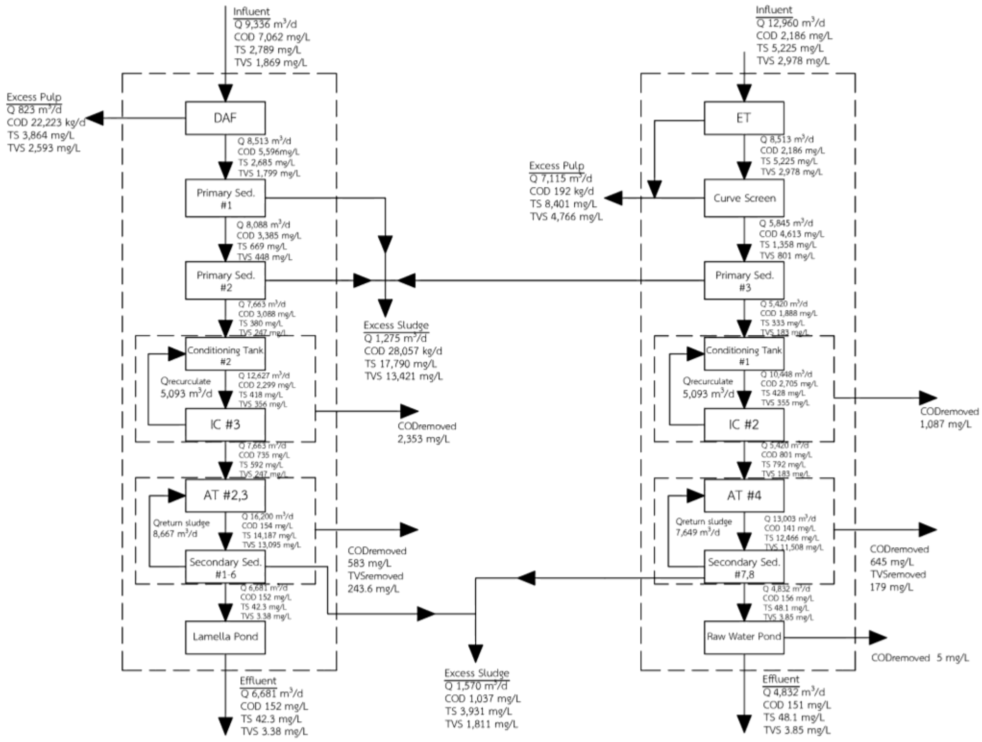
2.4 โรงจักรไฟฟ้า

กระบวนการเริ่มจากการคัดขนาดถ่านหินผ่านตะแกรง ก่อนเข้าสู่โรงบดถ่านหิน โดยถ่านหินจะถูกย่อยและทำให้แห้งด้วย Crusher Dryer จากนั้นผ่านการบดละเอียดด้วย Mill และแยกขนาดด้วย Classifier ถ่านที่ได้บางส่วนถูกเก็บในถังเก็บถ่านหิน (Coal Bunker) และอีกส่วนถูกส่งเข้าสู่โรงไฟฟ้า

ในส่วนของโรงไฟฟ้า น้ำที่ผ่านการปรับคุณภาพด้วยระบบ Softener จุดเตาเผาเริ่มต้นด้วยน้ำมันดีเซล และป้อนถ่านหินเข้าสู่เตาเผาแบบฟลูอิดไดซ์เบด โดยมี Primary Air เป็นตัวพยุงเชื้อเพลิงในการเผาไหม้ และ Secondary Air ที่ถูกให้ความร้อนผ่าน Steam Air Heater และ Gas Air Heater เพื่อช่วยเพิ่มประสิทธิภาพการเผาไหม้ มลพิษที่เกิดขึ้น เช่น Fly Ash และ Flue Gas จะถูกบำบัดด้วยระบบควบคุมมลพิษทางอากาศก่อนปล่อยออกสู่บรรยากาศ

ในการผลิตพลังงาน เมื่อ Boiler ผลิตไอน้ำแรงดันสูง (High Pressure Steam; 115 bar) จะถูกส่งไปยัง Turbine Generator 1 และ 3 เพื่อผลิตไฟฟ้าขนาด 11 kV ไอน้ำแรงดันสูงที่เหลือจะถูกลดความดันลงเหลือประมาณ 5.5 bar กลายเป็นไอน้ำแรงดันต่ำ (Low Pressure Steam) เพื่อนำไปใช้ในกระบวนการผลิตกระดาษรีไซเคิล และอีกส่วนหนึ่งถูกส่งเข้าสู่ Turbine Generator 2 และ 4 เพื่อผลิตกระแสไฟฟ้าเพิ่มเติมสำหรับใช้ในโรงงาน

3. ระบบบำบัดน้ำเสียของโรงงานกระดาษรีไซเคิล



รูปที่ ฉ.1 แผนผังการไหลของพารามิเตอร์ต่าง ๆ (COD, TS และTVS) ในระบบบำบัดน้ำเสียของโรงงานกระดาษรีไซเคิล

ภาคผนวก ช
บทความทางวิชาการที่ได้รับการตีพิมพ์เผยแพร่ในระหว่างการศึกษา

รายชื่อบทความที่ได้รับการตีพิมพ์เผยแพร่ในระหว่างศึกษา

บทความวิจัยที่ได้รับการตีพิมพ์ในวารสารวิชาการระดับนานาชาติ จำนวน 1 บทความ

Nammana, B., Racho, P., Nawong, S., Wichitsathian, B., & Tantrakarnapa, K. (2025). Feasibility of anaerobic co-digestion for biogas production from recycled paper industry sludge: optimization of mixing ratios and application in two-stage cstr system design. *Water Science & Technology, 92*(5): 683-703. Doi:10.2166/wst.2025.118

บทความวิจัยเต็มรูปแบบที่ได้รับการตีพิมพ์ในการประชุมวิชาการระดับนานาชาติ จำนวน 1 บทความ

Racho, P., Nammana, B., & Tantemsapya, N. (2024). Influence of sludge ratios and biokinetics leading to optimal design conditions for anaerobic co-digestion of excess sludge from the pulp and paper mill industry. *Proceedings of the 18th IWA World Conference on Anaerobic Digestion* (pp. 737-745). İstanbul: İTÜ Yayınevi.

Water Science & Technology

© 2025 The Authors Water Science & Technology Vol 92 No 5, 683 doi: 10.2166/wst.2025.118

Feasibility of anaerobic co-digestion for biogas production from recycled paper industry sludge: optimization of mixing ratios and application in two-stage CSTR system design

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ABSTRACT

Anaerobic co-digestion (AnCoD) presents a promising route for valorizing sludge generated from recycled paper processing. This study explored the co-digestion of primary sludge (PS) and secondary sludge (SS) at various mixing ratios to enhance methane generation and system stability. Batch biochemical methane potential (BMP) assays revealed that the 1:3 PS:SS ratio produced the highest methane yield (918.66 mL CH_4/g VS_fed) with a notably short lag phase of 1.59 days. Kinetic assessment using both modified Gompertz and logistic models indicated that the former offered superior fitting accuracy ($R^2 > 0.986$), effectively describing methane production dynamics. A two-stage continuous stirred-tank reactor (CSTR) system operated under this optimal ratio showed distinct functional separation: the acidogenic stage facilitated hydrolysis and volatile fatty acid (VFA) degradation, while the methanogenic stage supported biogas generation with stable pH and low VFA/alkalinity ratios. Microbial analysis confirmed a clear differentiation between fermentative and methanogenic communities, with evidence suggesting enhanced electron transfer pathways. These findings underscore the potential of AnCoD for efficient sludge stabilization and bioenergy recovery in the pulp and paper sector.

Key words: anaerobic co-digestion, biogas production, biokinetics, pulp and paper mill sludge, sludge digestion

HIGHLIGHTS

- 1:3 PS:SS ratio yielded 918.66 mL CH_4/g VS_fed with highest biogas efficiency.
- The modified Gompertz model showed a superior fit to the Modified Logistic model ($R^2 > 0.986$).
- Two-stage CSTR maintained stable pH and VFA/alkalinity with clear phase separation.
- *Bacillus cereus* dominated in optimal co-digestion.
- Findings support co-AD scale-up for recycled paper sludge under circular economy goals.

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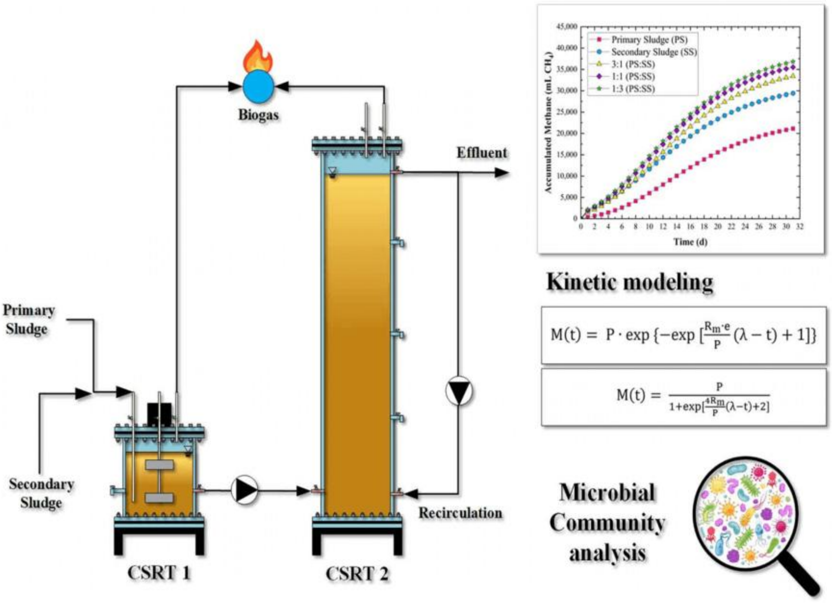
GRAPHICAL ABSTRACT



INTRODUCTION

The wastewater treatment systems in the paper industry generate substantial amounts of excess sludge, estimated to range from 200 to 400 kg/ton of paper (Balwaik & Raut 2011; Turner *et al.* 2022) and 40–50 kg of dry sludge/ton of paper (Mahmood & Elliott 2006; Jele *et al.* 2022). Typically, these sludges comprise approximately 70% PS and 30% SS. PS is generated during preliminary treatment processes, such as dissolved air flotation (DAF) or primary sedimentation. While a portion of PS can be repurposed for low-grade paper products, such as boards and crates, a significant quantity still requires proper disposal. SS, on the other hand, originates from secondary sedimentation tanks in activated sludge (AS) systems. Preliminary data from a paper mill in Samut Sakhon Province, Thailand, highlight the significant volume of excess sludge generated. This includes approximately 1,470 m^3/day or 25.87 tons (dry weight) of PS per day, and an average of 2,090 m^3/day or 36.83 tons (dry weight) of SS per day.

It is important to distinguish between paper sludge generated from virgin pulp production and recycled paper processing. Virgin pulp production generates sludge with relatively homogeneous properties and lower ash content due to fewer additives. In contrast, recycled paper sludge contains higher amounts of fillers (e.g., kaolin, calcium carbonate), printing inks, and synthetic binders, resulting in elevated ash content, lower biodegradability, and more variable chemical composition (Monte *et al.* 2009; Hubbe & Gill 2016). These characteristics make recycled paper sludge more difficult to treat using conventional biological processes, and thus it requires customized anaerobic digestion (AD) strategies. Furthermore, the increasing global demand for recycled paper – driven by environmental regulations, consumer preferences, and sustainability policies – has led to significant growth in the recycled paper market. According to market reports, the global recycled paper industry is projected to grow at a compound annual growth rate (CAGR) of over 5% through 2030 (Maximize Market Research 2024). As a result, understanding how to valorize waste from recycled paper production is becoming increasingly important for both industry and environmental management.

AD is the most common method for sludge stabilization. Moreover, this digestion process using various anaerobic bacteria produces biogas, including methane, that can be an alternative source of energy. AD has been successfully used for sludge treatments of various kinds, for example, sewage sludge, waste AS and cow manure. However, very few studies have applied AD for PS treatment due to its low nutrient content and poor biodegradability (Lopes *et al.* 2018).

Previous studies on the properties of excess sludge generated by the paper industry have highlighted notable characteristics of both PS and SS. Both types of sludge exhibit high moisture content, ranging from 53 to 77% (Simão *et al.* 2018). However, PS poses specific challenges due to its slow biodegradability, primarily attributed to its composition. It contains approximately 5.7% lignin, 32–81% cellulose, and 6.5–12% hemicellulose (Lopes *et al.* 2018; Simão *et al.* 2018). PS is also characterized by a total solids (TS) content of 32–80%, with volatile solids (TVS) making up 32–58% of TS. A significant portion of the TVS, approximately 55%, is composed of ash. Additionally, PS has a high chemical oxygen demand (COD) of around 64,300 mg/L (Lopes *et al.* 2018; Chakraborty *et al.* 2019). Despite the presence of organic matter, PS is nutrient-poor, with a carbon-to-nitrogen (C/N) ratio ranging from 32:1 to 930:1. This ratio significantly exceeds the optimal range of 20–30:1 required for efficient AD (Veluchamy & Kalamdhad 2017).

Given the characteristics of excess sludge from the paper industry, its integration into a co-anaerobic digestion (AnCoD) system presents a promising opportunity for resource recovery and waste management. The high organic content, particularly in PS, combined with the relatively low biodegradability, makes it an ideal candidate for AnCoD when paired with substrates rich in readily degradable organic matter and nutrients (Callahan 2023). Co-digestion helps balance the nutrient profile, especially the C/N ratio, optimize buffering capacity, and enhance microbial synergy, thereby improving methane yield and process stability (Mata-Alvarez *et al.* 2014; Syaichurrozi 2018).

Moreover, AD involves complex biochemical pathways including hydrolysis, acidogenesis, acetogenesis, and methanogenesis, each governed by specific microbial communities and sensitive to substrate properties. In co-digestion systems, synergistic effects can occur when complementary substrates facilitate each stage of the biochemical process (Appels *et al.* 2008). For example, PS contributes high organic content (mainly lignocellulose), while SS contains more active microbial biomass and available nutrients, enhancing both hydrolytic and methanogenic steps.

Microbial community analysis in this study further revealed the predominance of key anaerobic groups such as *Methanosaeta* spp., *Methanosarcina* spp., *Clostridium* spp., and *Bacteroides* spp. in the optimal 1:3 PS:SS ratio. The presence of *Methanosaeta* and *Methanosarcina* is particularly important for acetoclastic and hydrogenotrophic methanogenesis, while *Clostridium* supports hydrolysis and acidogenesis. These findings align with improved methane production and shorter lag phases, indicating active syntrophic interactions within the system (Ziganshin *et al.* 2013; De Vrieze *et al.* 2015).

However, most existing studies have focused on either batch BMP testing or mono-digestion, with limited research investigating real industrial sludge co-digestion under continuous flow systems (Gievers *et al.* 2022). Additionally, biokinetic analyses often rely solely on Gompertz-type modeling without evaluating alternative models that may better reflect complex substrate degradation behaviors.

To address these gaps, this study was designed in two phases. The first phase involves batch tests using the biochemical methane potential (BMP) method to determine the optimal mixing ratio of PS and SS. These tests evaluate the synergistic effects of different proportions on digestion efficiency and biogas production while providing critical biokinetic parameters, such as methane yield, lag phase duration, and maximum methane production rate. The biokinetic data obtained from the BMP tests were used as the basis for designing the continuous anaerobic co-digestion (AnCoD) system, ensuring that the identified mixing ratios and microbial activity align with the requirements for stable and efficient operation.

The second phase focuses on operating a continuous two-stage continuous stirred-tank reactor (CSTR) system using the optimal sludge mixing ratio identified in the batch tests. This configuration allows for phase separation and improves acidogenesis-methanogenesis stability. The system's performance was evaluated under steady-state conditions by monitoring pH, volatile fatty acid (VFA)-to-alkalinity ratio, and organic matter removal efficiency.

In addition, a comparative kinetic analysis was performed using both the Modified Gompertz and Modified Logistic models to evaluate model accuracy and interpret microbial dynamics. The hypothesis of this study is that integrating PS and SS at an optimal ratio in a two-stage co-digestion system will enhance methane production and process stability, and that biokinetic behavior can be better captured using alternative models.

These contributions aim to fill key research gaps and demonstrate the feasibility of applying co-digestion to real-world paper industry sludge under scalable and sustainable conditions.

METHODS

Excess sludge: sample collection and storage

Excess sludge used in this study was obtained from a paper mill located in Samut Sakhon Province, Thailand, prior to the dewatering process. The collected samples comprised:

- PS: Retrieved from the primary sedimentation tank of the wastewater treatment system.
- SS: Collected from the secondary sedimentation tank of the AS biological treatment system.

Following collection, all sludge samples were stored at 4 °C to preserve their physicochemical integrity for subsequent analyses. These included characterization of physical and chemical properties (as summarized in Table 1), assessment of biodegradability, BMP testing, and performance evaluation in a two-stage CSTR system.

Batch experiments

This study aims to evaluate the biodegradability and BMP of excess sludge generated from recycled paper production through both mono-digestion and co-digestion approaches. Batch experiments were conducted under mesophilic conditions (35 ± 5 °C) using various volumetric ratios of PS to SS, including 1:0 (PS only), 3:1, 1:1, 1:3, and 0:1 (SS only). These ratios were selected to investigate synergistic effects on organic matter degradation and methane yield. The initial pH of the digestion medium was carefully adjusted and maintained at 7.00 ± 0.02 throughout the experiments. All experiments were conducted in triplicate ($n = 3$).

Biodegradation experiments

The COD of the sludge was fractionated into four components, as illustrated in Figure 1, following the method described by Wentzel *et al.* (1995). These components included slowly biodegradable COD (BPCOD), which plays a critical role in anaerobic conversion pathways. Total COD (TCOD) was determined using standard procedures, while biological oxygen demand over 20 days (BOD_{20}) was measured under inhibited nitrification conditions using an OxiTop®-C measuring head (Boursier *et al.* 2005). The biodegradable COD (BCOD) fraction was subsequently calculated using the TCOD and BOD_{20} values, following the procedure outlined by Boursier *et al.* (2005).

BMP reactor setup and operation

The biochemical methane potential (BMP) tests were conducted in batch-mode anaerobic reactors with an effective working volume of 4 L. Each reactor was connected to a gas collection system comprising an external container filled with 1.5 N sodium hydroxide (NaOH) solution, which served to absorb carbon dioxide (CO_2) and hydrogen sulfide (H_2S). Methane production was quantified by the displacement of the NaOH solution, as illustrated in Figure 2.

Table 1 | Physical and chemical characteristics of primary sludge and secondary sludge (Mean ± SD)

Characteristic	PS	SS
pH	6.02 ± 0.00	7.46 ± 0.03
Moisture (%)	95.41 ± 0.77	99.70 ± 0.01
Total COD (mg/L)	67,904 ± 1,575	10,653 ± 2,232
Soluble COD (mg/L)	10,774 ± 6,494	7,407 ± 1,166
Total solids (mg/L)	24,390 ± 127	13,790 ± 1,626
Total suspended solids (mg/L)	19,550	11,340
Total volatile solids (mg/L)	15,010 ± 240	4,340 ± 665
Total Kjeldahl nitrogen (mg NH_4-N/L)	37.35 ± 2.89	37.64 ± 1.65
Alkalinity (mg $CaCO_3$/L)	7,380 ± 355	752 ± 118
Volatile fatty acid (mg CH_3COOH/L)	2,341 ± 116	1,225 ± 53
C/N	1,840	274
$TBOD_{20}$/TCOD	0.35	0.83
$TBOD_5$/TCOD	0.23	0.40

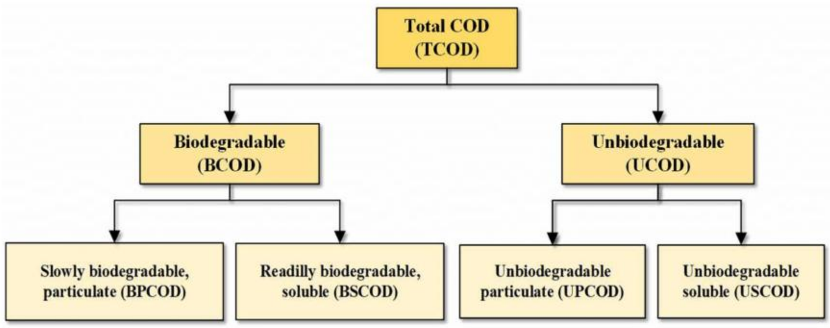


Figure 1 | COD fractionation of sludge.

All reactors were maintained under mesophilic conditions at a constant temperature of 35 ± 1.0 °C. Prior to gas volume measurements, each reactor was manually agitated for 1 min to ensure homogeneity. The digestion period was set to a hydraulic retention time (HRT) of 31 days.

All experimental sets were inoculated with anaerobic microbial sludge at a concentration of 2 g VS/L, following the method described by Rajput & Sheikh (2019), to ensure uniform microbial activity across all treatments. The initial pH of each reactor was adjusted to 7.00 ± 0.01 using either hydrochloric acid (HCl) or sodium hydroxide (NaOH), and sodium bicarbonate ($NaHCO_3$) was added as a buffering agent.

Anaerobic conditions were established by purging each reactor with nitrogen (N_2) gas for 3 min. Gas volumes were measured by collecting the displaced NaOH solution in a graduated syringe. The cumulative methane production was recorded daily throughout the experiment.

Kinetic modeling of methane production

The actual methane production in each experimental set was determined by subtracting the methane volume generated from the blank control. The specific methane yield was calculated relative to the amount of volatile solids (VS) added per HRT during the BMP test.

The experimental data were used to plot the cumulative methane production curve over time. Kinetic modeling was conducted using two well-established models: the modified Gompertz model (Lay *et al.* 1996) and the modified logistic model (Zwietering *et al.* 1990). These models were used to describe the methane production kinetics and to estimate key parameters including the methane production potential (P), maximum methane production rate (R_m), and lag phase duration (λ). Curve fitting and parameter estimation were performed using SPSS software, and the goodness-of-fit of each model was assessed using the coefficient of determination (R^2).

The modified Gompertz model is expressed as follows:

$$M(t) = P \cdot \exp\left\{-\exp\left[\frac{R_m \cdot e}{P}(\lambda - t) + 1\right]\right\} \quad (1)$$

where $M(t)$ = cumulative methane production at time t (mL CH_4); P = methane production potential (mL CH_4); R_m = maximum methane production rate (mL CH_4/day); λ = lag phase (d); e = Euler's number (~2.718).

The modified logistic model is given by:

$$M(t) = \frac{P}{1 + \exp\left[\frac{4R_m}{P}(\lambda - t) + 2\right]} \quad (2)$$

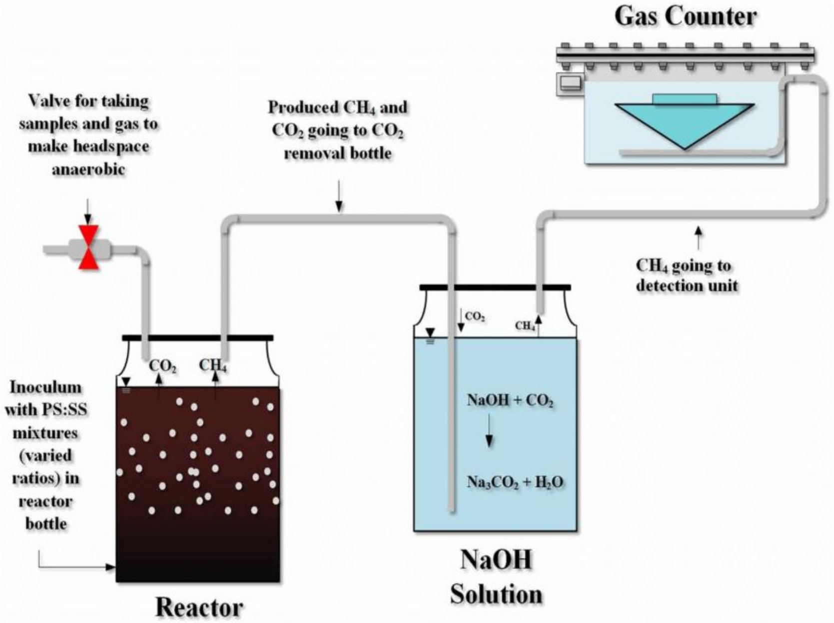


Figure 2 | BMP test setup: (1) reaction tank, (2) NaOH trap, (3) gas collection container.

This model provides a sigmoidal description of methane accumulation and has been shown to accurately fit methane production data under various substrate conditions (Zwietering *et al.* 1990).

Two-stage anaerobic co-digestion in continuous operation

Based on the findings obtained from the BMP tests, a two-stage CSTR system was developed to evaluate the anaerobic co-digestion (AnCoD) of PS and SS generated from the paper industry. The operational parameters employed in this system are summarized in Table 2.

The experimental setup was implemented under semi-continuous feeding conditions at Suranaree University of Technology, as illustrated in Figure 3. In this configuration, the first reactor (CSTR 1) was designated as the hydrolysis–acidogenesis tank, while the second reactor (CSTR 2) was operated as the methanogenic phase for biogas production.

The CSTR 1 was equipped with a mechanical impeller to ensure thorough mixing, whereas CSTR 2 utilized an internal recirculation system to facilitate uniform flow distribution and maintain anaerobic conditions. Both reactors were connected to individual gas counters for continuous biogas volume measurement.

The optimal 1:3 PS:SS blend was identified through BMP assays, maximizing methane yield and biodegradability. HRT of CSTR 1 was calibrated using the lag phase duration (λ) specific to this substrate ratio, while HRT of CSTR 2 was determined from the intersection of the R_m (maximum methane production rate) and P (cumulative methane production) axes in bio-kinetic modeling of the same blend. This dual-metric approach ensured phase-specific retention times aligned with microbial kinetic thresholds, enhancing system stability and biogas output efficiency in lignocellulose-rich digestion systems.

The start-up process commenced by seeding both reactors with anaerobic inoculum at 10% of the effective working volume, in accordance with the recommendation by Hobson & Wheatley (1993). CSTR 1 and CSTR 2 had working volumes of 3.0 and 22.5 L, respectively, and were seeded with 0.3 and 2.25 L of inoculum. The inoculum was sourced from the anaerobic sludge of a cassava starch wastewater treatment system in Nakhon Ratchasima Province, Thailand.

Table 2 | Operational parameters for two-stage anaerobic co-digestion of primary and secondary sludge

	Operating conditions	
Parameters	**CSTR 1**	**CSTR 2**
PS:SS ratios	1:3	–
Volume reactor (L)	3	22.5
Dimeter (cm)	15.24 (6″)	15.24 (6″)
Height (cm)	19	126.81
HRT (days)	1.6	24
Flow rate (L/day)	1.875	0.9375
Recirculation rate (L/day)	–	84
OLR (kg TVS/m^3-day)	6.65	0.21

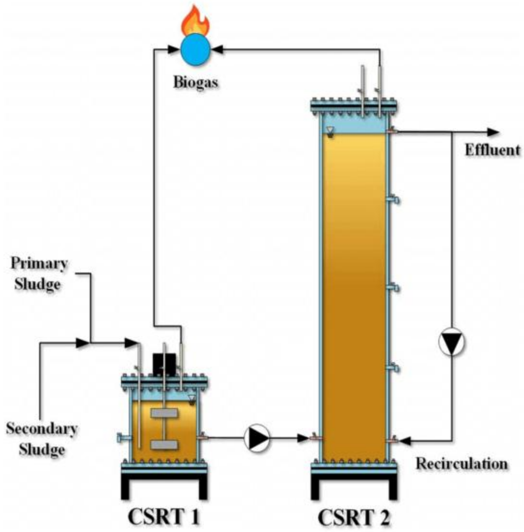


Figure 3 | Installation of a two-stage continuous stirred-tank reactor (CSTR) system.

The system was operated in a semi-continuous feeding mode. Mixed sludge was fed and withdrawn daily in equal volumes to maintain a constant HRT. For CSTR 1, 1.640 L of feed was added and withdrawn each day. The effluent from CSTR 1, following hydrolysis and acidogenesis, was used as the influent for CSTR 2, at a volume of 820 mL per day.

CSTR 1 was equipped with a mechanical impeller to maintain uniform mixing. CSTR 2 employed an internal recirculation system wherein both effluent and a portion of the generated biogas were recirculated. This mechanism enhanced contact between microorganisms and substrate, reduced the risk of stratification, and promoted stable methanogenic activity.

Each reactor underwent a daily 2-h settling phase to allow solid–liquid separation prior to effluent withdrawal. Effluent samples from both reactors were analyzed for a range of parameters, including pH, moisture content, total chemical oxygen demand (TCOD), soluble COD (SCOD), TS, total suspended solids (TSS), TVS, total Kjeldahl nitrogen (TKN), alkalinity, and volatile fatty acids (VFA). All analyses followed the Standard Methods for the Examination of Water and Wastewater (American Public Health Association, American Water Works Association, & Water Environment Federation (2012)).

Biogas production was measured daily using a gas counter, and the volume was calculated based on the number of revolutions.

Microbial community analysis

Mixed microbial cultures were collected from the two-stage CSTR system and serially diluted from 10^0 to 10^9, with each dilution plated in duplicate onto nutrient agar (NA) using the spread plate technique, as described by Madigan *et al.* (2020). Plates were incubated at 35 °C for 24 h to promote colony development. To investigate the influence of methanol as a carbon source, parallel cultures were also established on NA supplemented with 1% methanol, which supports the growth of methanotrophic and methylotrophic bacteria (Nakagawa *et al.* 2012). Incubations were performed at both 28 and 35 °C to assess the effect of temperature on microbial diversity and growth. Following incubation, plates with well-separated colonies were selected for further analysis to facilitate pure culture isolation. Colony morphology was documented, and representative isolates were subjected to Gram staining and examined under a light microscope to assess cellular and colony characteristics (Gibbs & Hayes 1988).

For species-level identification, selected isolates underwent matrix-assisted laser desorption/ionization time-of-flight mass spectrometry (MALDI-TOF MS) analysis, following the protocol outlined by Zakavi *et al.* (2022). Briefly, single colonies were prepared using the direct transfer method with formic acid extraction. Mass spectra were acquired using Flexcontrol v. 3.4 software, and protein mass fingerprints were analyzed within a 300 ppm mass tolerance. The resulting spectra were processed with MALDI Biotyper Realtime Classification (RTC) v. 4.0, and identifications were assigned based on manufacturer-recommended score thresholds: scores of 2.000–3.000 indicated highly probable species identification, 1.700–1.999 indicated probable genus identification, and 0.000–1.699 were considered unreliable. Only isolates with scores $\geq$2.0 were considered confidently identified at the genus or species level (Zakavi *et al.* 2022). The MALDI-TOF MS analysis was performed at the Synchrotron Light Research Institute (SLRI), Thailand, which provided access and technical support for microbial identification. Data on microbial diversity and abundance were visualized using tables and graphs to compare the effects of methanol supplementation and incubation temperature on community structure.

RESULTS AND DISCUSSION

Biodegradability of excess sludge

The biodegradability of excess sludge from the recycled paper industry was evaluated through the fractionation of COD into specific components, following the methodology of Wentzel *et al.* (1995). These components include total COD (TCOD), biodegradable COD (BCOD), and slowly biodegradable COD (BPCOD), as presented in Figure 1. The TCOD was determined through standard analytical techniques, while the BOD_{20} was measured using an OxiTop®-C measuring head under nitrification-inhibited conditions (Boursier *et al.* 2005). The BCOD was subsequently calculated using the TCOD and BOD20 values.

The physical and chemical characteristics testing of excess sludge generated from the wastewater treatment system of the pulp and paper industry, outlined in Table 1, reveals that both PS and SS exhibit remarkably high moisture content. This is attributed to the fact that the excess sludge collected represents the initial discharge from both the primary and the biological sedimentation tanks, which has not undergone the water separation process. This high moisture content is beneficial for the biogas digester. The TVS content of PS and SS ranges from 42 to 62% TS and 28 to 31% TS, respectively. Moreover, it was noted that the organic content in PS is approximately two to three times higher than that in SS, consistent with the findings of Simão *et al.* (2018). Specifically, the organic content of PS and SS ranges between 36–47.8 and 35–76.1%, respectively.

However, the biodegradation of only PS presents challenges due to the complex structure of fibers and cellulose, as well as excessive organic loading for the anaerobic digester. According to Veluchamy & Kalamdhad (2017), the high lignin and cellulose content in PS limits microbial access and reduces hydrolysis efficiency. Lopes *et al.* (2018) further emphasized the recalcitrant nature of PS, highlighting its low solubilization rate without co-substrates. Bokhary *et al.* (2021) reported that combining PS with nitrogen-rich substrates can improve the C/N balance and enhance microbial metabolism. Similarly, Bayr & Rintala (2012) demonstrated that co-digestion improves the overall methane yield from fiber-rich sludges. Sun *et al.* (2022) also confirmed that mixed sludges perform better in terms of VFAs conversion and microbial stability under mesophilic conditions.

Moreover, the nutrient content in PS sludge is relatively low, characterized by a significantly higher C/N ratio than the ideal range. Typically, the appropriate C/N ratio for AD systems falls within the range of 20–30 (Veluchamy & Kalamdhad 2017). A high C/N ratio can result in rapid nitrogen depletion by methanogenic bacteria during protein synthesis, thereby limiting their ability to react further with the remaining carbon in the substrate. Consequently, this can lead to lower biogas production rates. In contrast, SS sludge exhibits high nutrient content, primarily nitrogen, resulting in a considerably lower C/N ratio compared to PS sludge. Additionally, both PS and SS demonstrate pH values ranging from 6.02 to 7.46, indicating a relatively neutral pH.

The assessment results of the COD fractions in the mixed sludge from the paper industry, with mixing ratios of 1:0 (only PS), 3:1, 1:1, 1:3, and 0:1 (only SS), reveal varying $TBOD_{20}/TCOD$ ratios of approximately 0.35, 0.40, 0.48, 0.58, and 0.83, respectively. These ratios indicate that in the mixing ratios of 1:0, 3:1, and 1:1, the organic matter present in the form of TCOD is predominantly difficult to biodegrade. Furthermore, the $SBOD_{20}/SCOD$ ratios are approximately 0.87, 0.97, 0.95, 0.95, and 0.70, respectively, suggesting that the organic matter in the form of soluble substances can be relatively easily biodegraded across all mixing ratios. Racho & Pongampornnara (2020) specifies that a BOD/COD ratio >0.45 indicates good biodegradability, 0.30–0.45 indicates relatively good biodegradability, 0.20–0.30 indicates some biodegradability, and if less than 0.20, the wastewater is not suitable for biological degradation. Based on these criteria, the findings suggest that the mixed sludge with ratios closer to 1:0 (only PS) and 3:1 exhibit relatively good biodegradability, while the ratios closer to 0:1 (only SS) may have limited biodegradability potential.

From Figure 4, it is evident that the mixing ratios of 1:3 and 0:1 result in predominantly biodegradable COD fractions, constituting 57.55 and 82.75%, respectively, of the total TCOD in the sludge. This indicates a higher proportion of SS compared to PS. Further breakdown shows that in the mixing ratios of 1:3 and 0:1, the biodegradable fraction is divided into BSCOD (rapidly biodegradable fraction), comprising 23.18 and 8.41%, respectively, and BPCOD (slowly biodegradable fraction), comprising 34.37 and 74.34%, respectively, of the total TCOD in the sludge. Consequently, the proportion of COD that cannot be biodegraded is only 42.45 and 17.25%, respectively, of the total TCOD. These findings suggest that sludge with mixing ratios of 1:3 and 0:1 possesses a high proportion of biodegradable fractions, as most of the organic matter is biodegradable, with unbiodegradable fractions, primarily found in PS, present in lesser proportions. This makes the sludge suitable for biogas production.

BMP test results

The investigation into evaluating the influence of different PS:SS ratios on BMP Test indicated that the maximum potential methane production was observed at varying proportions of 1:0, 3:1, 1:1, 1:3, and 0:1, with corresponding values of 23,684,

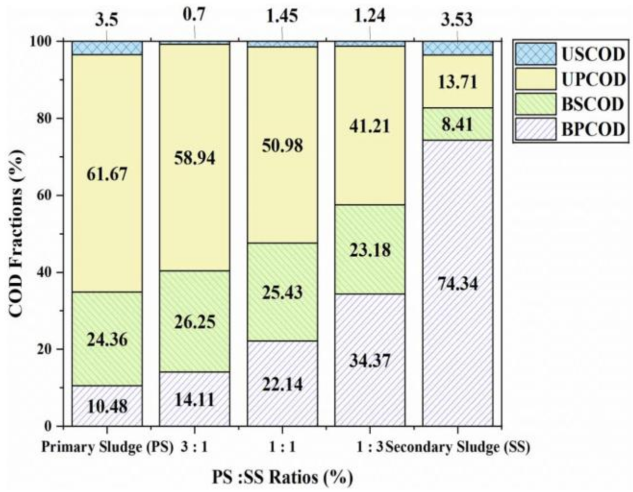


Figure 4 | The COD fractions in various PS:SS mixing ratios.

36,394, 38,510, 39,973, and 32,188 mL CH_4, respectively, as illustrated in Figure 5(a). Of note is the proportion of 1:3, which demonstrated superior methane production potential compared to other co-digestion ratios and even outperformed the single-substrate digestion of PS and SS. The daily measurement of gas volume within the system enabled the computation of cumulative methane gas production for each blending ratio under investigation. Subsequently, these findings were subjected to analysis using the modified Gompertz equation (Lay *et al.* 1996) through the utilization of SPSS software, leading to the generation of predictive experimental outcomes, as illustrated in Figure 5(b)–5(f).

When considering the methane production potential (CH_4 Yield) from experiments with various mixing ratios, as shown in Table 3, it is evident that at the proportions of 1:0, 3:1, 1:1, 1:3, and 0:1, the methane production potentials are 315.43, 576.96, 689.66, 918.66, and 1,170.59 mL CH_4/g VS_fed, respectively. This study reveals that SS exhibits a higher methane production potential compared to other mixing ratios, consistent with the fact that SS has a higher proportion of particulate biodegradable COD than other mixtures. However, the mixing ratio of 1:3 demonstrates a higher production potential than other mixtures, including single-substrate digestion of PS, which, at a 1:3 ratio, still has a lower proportion of particulate biodegradable COD than single-substrate digestion of SS.

Mechanistically, this enhanced methane production at the 1:3 ratio may be attributed to synergistic effects from co-digestion, which improves nutrient balance, buffering capacity, and microbial community diversity (Ferdeș *et al.* 2023). The inclusion of SS contributes nitrogen and readily biodegradable components, helping to reduce the lag phase and accelerate methanogenesis. Recent studies have indicated that co-digestion with nutrient-rich substrates not only enhances hydrolysis but also supports syntrophic interactions between fermentative bacteria and methanogens, which are essential for stable and efficient biogas production (Sharma *et al.* 2024). Additionally, the balanced PS:SS ratio at 1:3 promotes more favorable

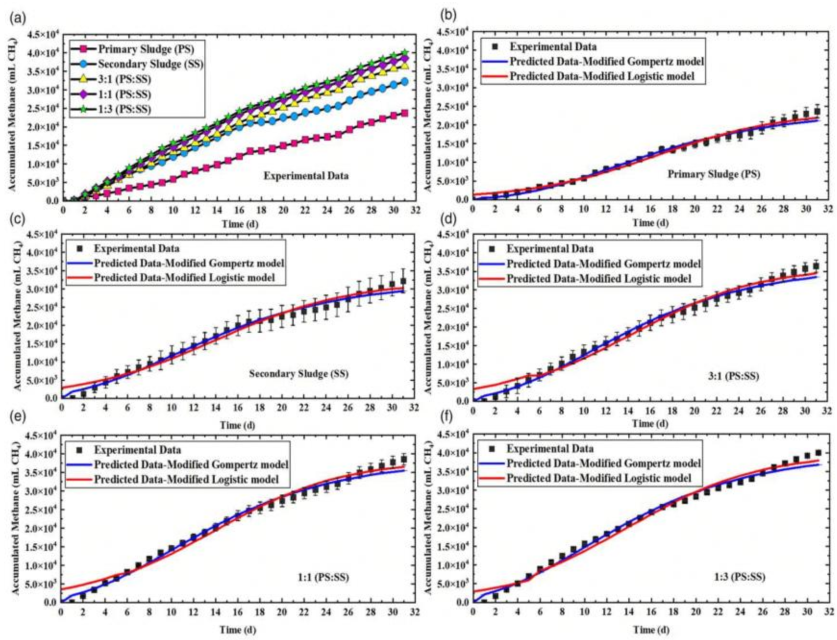


Figure 5 | Cumulative methane production from sewage sludge co-digestion experiments: (a) comparison of different sludge mixing ratios, (b–f) model fitting comparison between experimental data, modified Gompertz model, and modified logistic model for primary sludge (PS), secondary sludge (SS), and various PS:SS ratios (3:1, 1:1, 1:3).

Table 3 | Kinetic value for co-digestion of excess sludge from the pulp and paper mill industry with different PS:SS ratios

PS:SS ratio	Model	CH_4 yield (mL CH_4/g VS_{fed})	P (mL CH_4)	R_m (mL CH_4/day)	λ (day)	R^2
1:0	Modified Gompertz	315.43	23,684	1,030	4.21	0.986
	Modified logistic			1,028	5.02	0.988
3:1	Modified Gompertz	576.96	36,394	1,614	2.29	0.989
	Modified logistic			1,571	2.82	0.985
1:1	Modified Gompertz	689.66	38,510	1,703	1.73	0.990
	Modified logistic			1,643	2.15	0.984
1:3	Modified Gompertz	918.66	39,973	1,750	1.59	0.989
	Modified logistic			1,687	1.99	0.982
0:1	Modified Gompertz	1,170.59	32,188	1,366	1.46	0.987
	Modified logistic			1,317	1.85	0.978

The resulting data obtained through fitting to Gompertz model utilizing the SPSS program.

VFAs profiles, reducing acidification risks and stabilizing the pH within the optimum range for *Methanogenic archaea* (Wainaina *et al.* 2019).

This finding aligns with the research conducted by Sun *et al.* (2022), which found that AD of SS alone yields higher methane production compared to PS. Moreover, in mixed PS and SS, it is found that at a mixing ratio of 1:3, there is a higher potential than ratios of 3:1 and 1:1. Statistical analysis using a paired two-sample *t*-test revealed that the average methane yield at the PS:SS ratio of 3:1 was significantly different from those at the 1:1 and 1:3 ratios ($p < 0.05$), indicating a substantial impact of substrate composition on biogas production potential. Additionally, a significant difference ($p < 0.05$) was also observed between the 1:1 and 1:3 ratios, further confirming that variations in sludge mixing ratios influence the overall methane generation efficiency.

These outcomes are comparable with several recent studies. For example, Jo *et al.* (2024) reported enhanced methane production from co-digestion of cattle manure and food waste at specific mixing ratios, highlighting the importance of optimizing substrate synergy. Similarly, Siddique & Wahid (2018) found that appropriate feedstock proportions can significantly improve CH_4 yield due to improved C/N ratios and buffering capacity. In another study, Mu *et al.* (2020) achieved higher biogas production from sludge co-digested with kitchen waste at a 1:3 ratio, which closely mirrors the present findings. Furthermore, Kumar *et al.* (2020) demonstrated that co-digestion of textile sludge and agricultural residues at balanced ratios increased the biodegradability index and methane potential. Lastly, Chow *et al.* (2020) reported that pre-treated mixed sludge with optimized ratios showed superior methane yields, confirming that co-digestion can overcome individual feedstock limitations.

Comparative evaluation of kinetic models

In this study, both the modified Gompertz and modified logistic models were applied to evaluate the kinetics of methane production during the anaerobic co-digestion of recycled paper industry sludge.

Modified Gompertz model performance

The biokinetics analysis presented in Table 3 reveals that the modified Gompertz model effectively captured the cumulative methane production profiles across all tested PS:SS mixing ratios. Notably, the mixture ratio of 1:3 yielded the highest methane yield at 918.66 mL CH_4/g VS_fed, accompanied by a lag phase duration of 1.59 days. This relatively short lag phase can be attributed to the hydrolysis of constituents that are not readily biodegradable. Moreover, this ratio exhibited the highest methane production rate (R_m) of 1,750 mL CH_4/day, indicating favorable substrate availability and microbial activity.

Mechanistically, the Gompertz model assumes a sigmoid response reflecting microbial adaptation (λ), exponential growth (R_m), and substrate saturation (P). The high R^2 values (0.986–0.990) in this study support the notion that the co-digested PS:SS mixtures reached microbial adaptation quickly and sustained methanogenic activity. The elevated methane yield at the 1:3 ratio may be attributed to a more balanced C:N ratio (~26.4), enhanced buffering capacity, and greater availability of readily fermentable COD (initial SCOD/TCOD ~47%) – a finding consistent with Lay *et al.* (1997) and Mata-Alvarez *et al.* (2000), who reported improved kinetics with optimally pre-treated or blended substrates.

The results are comparable to the findings by Gievers *et al.* (2022), who demonstrated that co-digestion of paper sludge can enhance methane generation and reduce lag phases under optimized mixing conditions. Although their study used a different substrate combination and system configuration, the trends in methane yield and biokinetics were similar. In addition, Kumsiri *et al.* (2021) reported similar improvements in methane kinetics when paper sludge was co-digested with food waste, noting reduced lag phases and increased R_m under optimized ratios. Likewise, Ma *et al.* (2025) confirmed that co-digestion with nitrogen-rich sludge enhanced the microbial hydrolysis rate and kinetic parameter stability across trials.

Modified logistic model performance

The modified logistic model exhibited exceptional predictive accuracy for asymmetric methane production curves, achieving R^2 values of 0.978–0.988 and R_m 1,028–1,687 mL CH_4/day (Table 3). This performance highlights its capability to simulate substrate heterogeneity-driven dynamics, where spatially segregated hydrolytic (e.g., *Clostridium spp.* activity) and methanogenic phases (*Methanosaeta* dominance) create nonlinear kinetics (Cebeci *et al.* 2019; Gong *et al.* 2019). The model's asymmetric sigmoidal structure directly correlates with substrate accessibility gradients, as demonstrated by the 23% longer lag phases in low-SS systems compared to PS:SS 1:3 conditions – a phenomenon attributed to rate-limiting hydrolysis in cohesive substrates.

Validation against previous studies supports the model's reliability across critical bioconversion phases. Sanae *et al.* (2022) reported a 79% reduction in lag phase duration, from 5.46 to 1.04 h, following thermal pretreatment. This is consistent with our observed lambda value of 1.99 days in PS to SS co-digestion systems at a 1–3 ratio. Similarly, Gong *et al.* (2019) showed that SS-enriched substrates increased VFA production by 1.8 times during secondary fermentation, which supports the model's accuracy in capturing transitional phase behavior.

Comparative studies in the literature, including those by Cebeci *et al.* (2019), Gong *et al.* (2019), Sanae *et al.* (2022), consistently report that the modified Gompertz model is generally more suitable for kinetic analysis of AD systems, particularly those involving heterogeneous substrates and multi-phase microbial dynamics. This preference is typically supported by slightly higher coefficients of determination and lower fitting errors reported for the Gompertz model in such contexts.

Comparative interpretation

Given these findings, the modified Gompertz model could serve as a complementary or alternative kinetic tool for predicting methane yields in complex sludge-based systems. Its superiority in fitting cumulative methane production curves underlines its adaptability to substrate heterogeneity and metabolic succession, especially under two-stage CSTR configurations where spatial microbial stratification enhances phased degradation. The observed differences between the two models emphasize the importance of selecting modeling approaches that not only provide statistical accuracy but also reflect underlying biological processes.

Performance of the two-stage CSTR

The 1:3 PS:SS ratio was selected not only for its high methane yield (918.66 mL CH_4/g VS_fed), but also to ensure the co-utilization of both sludge types, reducing treatment costs while improving biodegradability and buffering capacity. Although SS alone (0:1) yielded more methane, it excludes PS, which poses disposal challenges. Co-digestion thus offers a more holistic and cost-effective solution aligned with circular economy goals.

To match microbial kinetics, HRT in CSTR 1 was based on the lag phase ($\lambda = 1.59$ days), while HRT in CSTR 2 was set from the intersection of R_m and P values from Gompertz modeling. This dual-parameter design ensured stable operation and efficient biogas recovery from lignocellulose-rich substrates.

The characterization of influent and effluent from the two-stage CSTR system demonstrated significant variations in physicochemical properties, highlighting the system's efficiency in organic matter removal and sludge stabilization. These operational outcomes are indicative of phase-specific biochemical transformations occurring within the acidogenic and methanogenic reactors. A detailed summary of the influent and effluent parameters is presented in Table 4.

The pH profile of the two-stage CSTR system, as depicted in Figure 6(a), underscores the efficiency of the system in differentiating the acidogenesis and methanogenesis phases. The influent exhibited a relatively stable pH within a slightly acidic range of 6.6–7.1, indicative of consistent feedstock characteristics. In CSTR 1, the pH increased slightly to a range of 6.64–7.33, reflecting active acidogenesis and sufficient buffering capacity to mitigate excessive acid buildup. Conversely,

Table 4 | Characterization of influent and effluent in a two-stage CSTR system (mean ± SD)

Characteristic	Influent	Effluent
PS:SS mixed	1:3	–
pH	6.96 ± 0.16	7.25 ± 0.18
Moisture (%)	–	–
Total COD (mg/L)	42,019.17 ± 12,888.14	20,553.98 ± 7,146.08
Soluble COD (mg/L)	23,911.17 ± 8,304.86	10,113.77 ± 5,245.92
Total solids (mg/L)	35,469.62 ± 17,193.44	1,727.25 ± 882.73
Total suspended solids (mg/L)	–	–
Total volatile solids (mg/L)	10,640.89 ± 5,158.03	518.17 ± 264.82
Total Kjeldahl nitrogen (mg NH_4-N/L)	64.18 ± 22.21	34.33 ± 12.01
Alkalinity (mg $CaCO_3$/L)	2,134.37 ± 377.81	2,674.89 ± 335.66
Volatile fatty acid (mg CH_3COOH/L)	1,460.18 ± 468.68	585.89 ± 276.26
C/N	845.27 ± 758.93	655.15 ± 333.90
$TBOD_{20}$/TCOD	–	–
$TBOD_5$/TCOD	–	–

CSTR 2 maintained a consistently higher and more stable pH range of 6.91–7.58, creating optimal conditions for methanogenesis. Statistical analysis using a *T*-test confirmed a significant difference in pH between CSTR 1 and CSTR 2 at a 95% confidence level ($p < 0.05$), validating the distinct metabolic activities in each reactor.

These findings align with those reported by Meghana & Shastri (2020), who observed distinct pH separation between acidogenic and methanogenic reactors in two-stage systems treating high-strength industrial wastewater. Similarly, Sun *et al.* (2020) emphasized that maintaining pH above 6.8 in methanogenic reactors is critical for methanogen viability and methane production. Effective pH regulation in this study is also consistent with previous findings that highlight the role of inherent buffering agents such as bicarbonates and feedstock alkalinity in mitigating system acidification (Rau 2008).

The VFA-to-alkalinity ratio, as illustrated in Figure 6(d), exhibits a decreasing trend as the flow progresses from the influent to CSTR 1 and subsequently to CSTR 2. In the influent, the ratio often exceeds 1, reflecting a high acid load, whereas in CSTR 2, it consistently drops below 1 after day 80. This reduction signifies the system's transition from an acidic environment to a well-buffered and stable condition, with a ratio below 1 in CSTR 2 indicating a healthy AD process where the buffering capacity effectively neutralizes acid production. This stabilization ensures system reliability and prevents inhibition caused by acid accumulation.

The observed trends in alkalinity increase, VFA reduction, and the decline in the VFA-to-alkalinity ratio across the two stages underscore the effectiveness of the two-stage CSTR system. CSTR 1 facilitates initial acid degradation, while CSTR 2 provides further stabilization and enhances biogas production. Similar trends were noted by Hasan *et al.* (2015), who reported that VFA/alkalinity ratios below 0.8 were correlated with high biogas yields and microbial stability. Moreover, Peters *et al.* (2021) demonstrated that two-stage reactors could more effectively manage acidification than single-stage configurations, particularly under variable loading rates. These results highlight the critical role of maintaining sufficient alkalinity to support microbial activity and mitigate acidification, particularly in anaerobic systems treating high-strength organic wastewater.

Figure 7(a) illustrates the trends in TVS removal efficiency across a two-stage CSTR system over time. The solid line represents the TVS removal efficiency (%), while the dashed line shows the effluent concentration. The system exhibits fluctuating removal efficiency, ranging from approximately 84.03 to 99.06%, suggesting dynamic operational performance. Periods of peak removal efficiency correspond with lower effluent concentrations, indicating a potential correlation between operational stability and TVS degradation efficiency. These observations align with those of Li *et al.* (2019), who found that efficient TVS removal is closely linked to reactor phase balance and effective microbial retention.

Figure 7(b) shows the trends in TCOD removal efficiency and effluent TCOD concentration over 220 days. The removal efficiency (%) varies significantly, with stable conditions yielding a value of 56.55 ± 17.88. This fluctuation is likely influenced

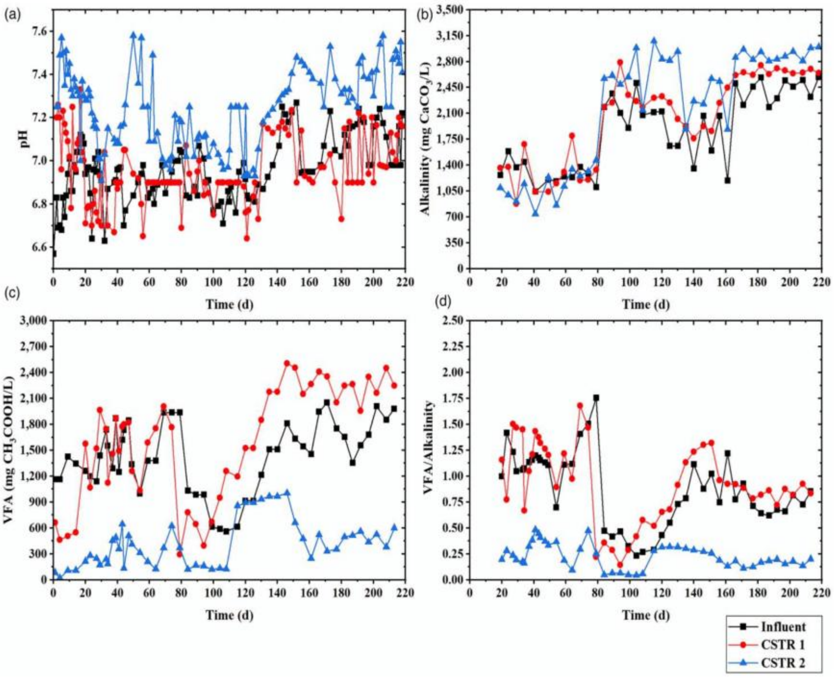


Figure 6 | (a) pH values, (b) Alkalinity ratio, (c) VFA values, and (d) VFA/Alkalinity ratio of the CSTR system.

by feedstock characteristics and reactor operational conditions. Effluent TCOD concentrations range from approximately 20,553.98 ± 146.08 mg/L, with inverse patterns observed in relation to removal efficiency. Periods of higher effluent concentrations coincide with dips in removal efficiency, highlighting the challenges of maintaining stable performance in multi-stage digestion systems. These findings are consistent with those of Tsegaye *et al.* (2023), who noted that variability in TCOD removal is often tied to organic load distribution and VFA accumulation in two-phase systems.

Figure 7(c) presents the removal efficiency of soluble chemical oxygen demand (SCOD) alongside effluent SCOD concentration. The SCOD removal efficiency exhibits a pattern like TCOD, with stable conditions showing a range of 56.80 ± 6.55 throughout the experimental period. Effluent SCOD concentrations vary from approximately 10,113.77 ± 5,245.92 mg/L. The trends suggest that the reactor's capacity to degrade soluble organics is sensitive to operational conditions, possibly influenced by feedstock variability or internal system dynamics. Enhanced SCOD removal efficiency is observed during periods of reduced effluent concentration, reinforcing the importance of optimizing system stability for effective organic matter degradation. These findings are supported by observations from Donoso-Bravo *et al.* (2015), who demonstrated that process stability directly enhances SCOD degradation kinetics in two-stage anaerobic systems.

The first two graphs in Figure 8 reveal insights into nitrogen dynamics, biomass concentration, and substrate utilization in the reactors. In Figure 9(a), TKN levels in CSTR 1 exhibit significant fluctuations, with peaks above 70 mg/L around days 110 and 170, indicating inconsistent nitrogen removal or varying substrate loads, while CSTR 2 demonstrates more stable TKN trends. Figure 9(b) complements this by showing that mixed liquor volatile suspended solids (MLVSS) concentration peaks dramatically (above 60,000 mg/L) around day 152, likely reflecting microbial growth stimulated by substrate accumulation. The inverse relationship between MLVSS and F/M highlights the balance between substrate availability and microbial

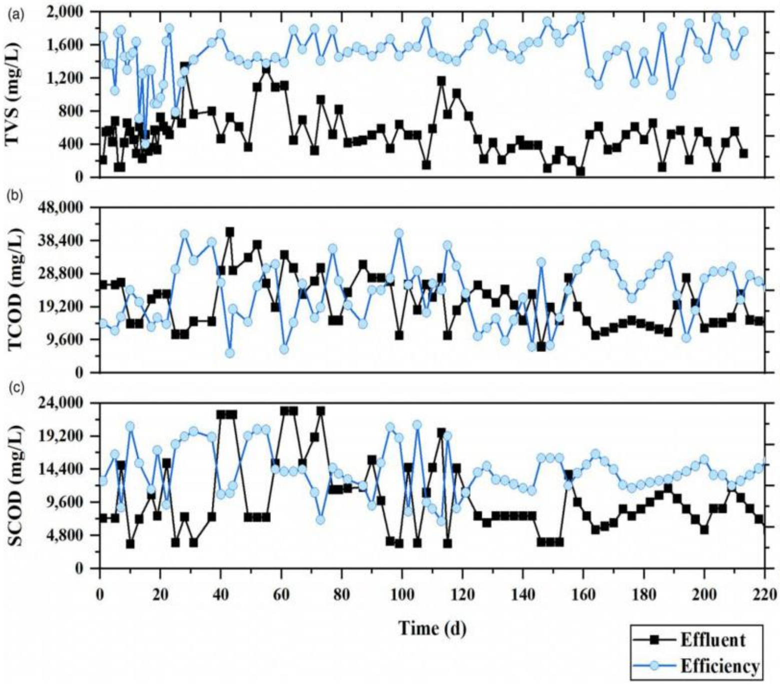


Figure 7 | Treatment removal efficiencies.

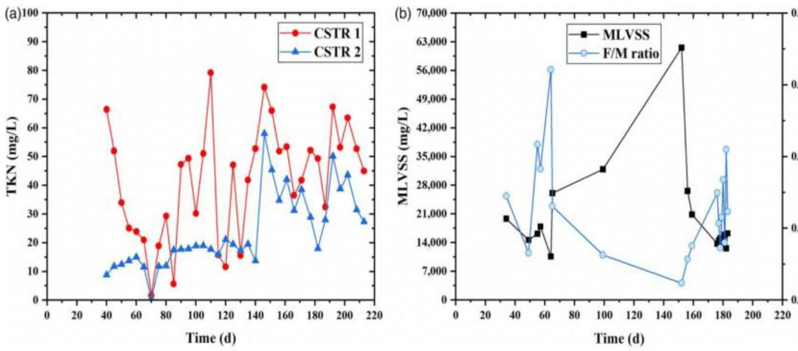


Figure 8 | (a) TKN values and (b) F/M ratio of the two-stage CSTR system.

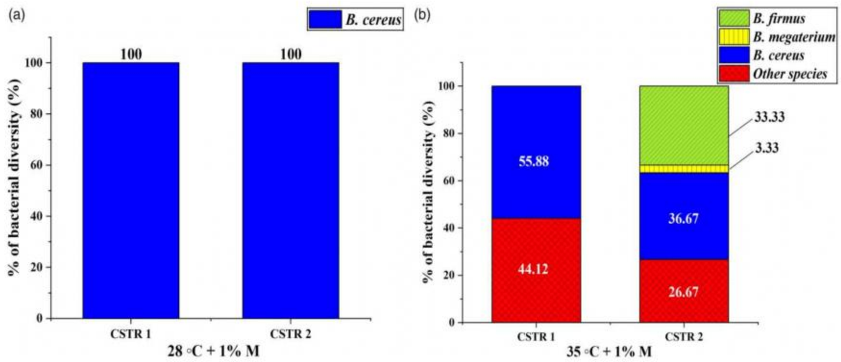


Figure 9 | Diversity of microbiome isolates collected from the two-stage CSTR system under methanol-supplemented conditions using MALDI-TOF MS: (a) incubated at 28 °C and (b) incubated at 35 °C.

activity, underscoring the reactors' operational dynamics. This pattern is in line with the findings of Chen *et al*. (2023), who reported that elevated biomass concentrations can suppress gas production if F/M ratio is not well balanced.

The biogas production results, as shown in Figure 6, indicate that CSTR 1 did not produce biogas throughout the entire operational period from the start. This was due to the low HRT, which prevented fermentation within the system. Additionally, no biogas production was observed in CSTR 2 during days 0–35, as this period was required for the acclimatization of the microbial community. Biogas production began on day 36, with an initial volume of 68 mL, and continued to increase, peaking at 2,545 mL as time progressed. However, the current average daily biogas production is 430 mL. This reduction is likely due to the high microbial concentration in the system, which may have resulted in a high food-to-microorganism (F/M) ratio, leading to a decrease in biogas production. The impact of microbial overpopulation on methanogenic inhibition has been similarly observed by Zhou *et al*. (2022).

In Table 5, the biogas production is examined across two continuous stirred-tank reactors (CSTR 1 and CSTR 2) under different operational conditions. The operational days were set to 220 days for both reactors. The co-substrate (PS:SS) feed rate varied, with CSTR 1 using 0.41 L/day and CSTR 2 using 1.23 L/day. The organic loading rate (OLR) was much higher in CSTR 1 (6.65 kg TVS/m^3-day) compared to CSTR 2 (0.21 kg TVS/m^3-day), indicating a more intensive substrate input in CSTR 1. The HRT was considerably shorter in CSTR 1 (1.6 days) than in CSTR 2 (24 days), which may reflect differences in the digestion rate and overall system design.

Table 5 provides insight into the operational performance of the reactors, particularly focusing on biogas yield. CSTR 2 achieved a biogas yield of 1.8 ± 0.48 mL biogas/g TVS_removed-day, reflecting moderate efficiency in substrate conversion

Table 5 | Summarizes the operational performance results

Parameters	CSTR 1	CSTR 2	Unit
Operating days	220	220	Days
Co-substrate (PS:SS)	0.41	1.23	L/day
OLR	6.65	0.21	kg TVS/m^3-day
HRT	1.6	24	Days
Working volume of digester	3	22.5	Litres
Biogas yield	–	1.8	TVS_removed-day ± S.D.
Biogas production	–	0.43 ± 0.13	L/day ± S.D.

Table 6 | Bacterial isolates, morphological and gram characteristics, MALDI-TOF MS identification, and population data in CSTR 1 and CSTR 2 of a two-stage CSTR system under different cultivation conditions (Mean ± S.D.)

Reactor	Condition	Isolate	Bacterial name	Morphological characterization	Gram staining	MALDITOF MS Score	Bacteria (×10^5 CFU/ml)	Total population (×10^5 CFU/ml)	VSS (g/L)	Number of bacteria gVSS^{-1} (×10^8)
CSTR 1	28 °C + 1% M[a]	1	*B. cereus*	Transparent, mucoid colony	+	2.189	5.65 ± 0.21	6.35 ± 0.7	4.32 ± 0.63	1.47
		2	*B. cereus*	Opaque with undulate margin	+	2.303	0.3 ± 0.42			
		3	*B. cereus*	Opaque with transparent margin, mucoid	+	2.238	0.4 ± 0.14			
	35 °C[b]	7	*B. cereus*	Opaque with undulate margin	+	2.001	2 ± 0.00	42.00 ± 2.2		9.72
		8	*S. maltophilia*	Transparent, mucoid colony	–	1.997	3 ± 1.24			
		9	*B. flexus*	Transparent with dull surface	+	1.899	36 ± 18.38			
		10	*B. licheniformis*	Mucoid, transparent, with undulate center	+	1.706	1 ± 1.41			
	35 °C + 1% M[c]	18	*A. schindleri*	Transparent, mucoid colony	–	1.715	7.5 ± 4.95	17.00 ± 0.6		3.94
		19	*B. cereus*	Opaque, circular colony	–	2.204	7 ± 2.83			
		20	*B. cereus*	Opaque with undulate margin	+	2.182	2.5 ± 2.12			
CSTR 2	28 °C + 1% M[a]	4	*B. cereus*	Transparent, mucoid colony	+	2.201	5.6 ± 1.27	6.55 ± 1.7	14.56 ± 1.22	0.45
		5	*B. cereus*	paque with undulate margin	+	2.260	0.35 ± 0.07			
		6	*B. cereus*	Opaque with transparent margin	+	2.312	0.6 ± 0.14			
	35 °C[b]	11	*B. pumilus*	Transparent, mucoid colony	+	1.631	0.5 ± 0.71	8.00 ± 4.0		0.55
		12	*B. megaterium*	Circular, opaque colony	+	1.516	2.5 ± 0.71			
		13	*B. pumilus*	Transparent, circular colony	+	1.757	1 ± 0.00			
		14	*B. pumilus*	Transparent with yellow pigmentation	–	1.749	1 ± 1.41			
		15	*B. subtilis*	White, mucoid colony	+	1.886	1.5 ± 2.12			
		16	*L. plantarum*	Transparent with undulate center	–	1.475	0.5 ± 0.71			
		17	*B. licheniformis*	Circular, transparent with dull surface	–	1.843	1 ± 0.00			
	35 °C + 1% M[c]	21	*B. subtilis*	Mucoid, transparent with undulate margin	–	1.739	4 ± 2.83	15.00 ± 0.8		1.03
		22	*B. cereus*	Opaque, circular, dull surface	+	2.200	5.5 ± 3.54			
		23	*B. megaterium*	Opaque, circular colony	+	2.232	0.5 ± 0.71			
		24	*B. firmus*	Transparent, circular colony	–	2.012	5 ± 1.41			

Note: CFU, colony forming units; VSS, volatile suspended solids. [a]Cultivated on nutrient agar (NA) with 1% methanol and incubated at 28 °C for 24 h.
[b]Cultivated on NA and incubated at 35 °C for 24 h.
[c]Cultivated on NA supplemented with 1% methanol and incubated at 35 °C for 24 h.

to gas despite its low OLR (0.21 kg TVS/m^3-day) and long HRT (24 days). The daily biogas production was 0.43 ± 0.13 L/day. The lack of biogas yield data for CSTR 1 prevents direct comparison, but its significantly higher OLR (6.65 kg TVS/m^3-day) and shorter HRT (1.6 days) suggest it prioritizes throughput over efficiency. These findings highlight the critical balance between operating conditions and biogas production efficiency, with optimization necessary to enhance gas yield and methane content.

Microbial community

The two-stage CSTR system demonstrated distinct functional stratification of microbial communities between reactors, with CSTR 1 primarily facilitating hydrolysis/acidogenesis and CSTR 2 supporting acetogenesis/methanogenesis (Table 6, Figure 9). In CSTR 1, *Bacillus cereus* dominated under all conditions (MALDI-TOF MS scores: 2.189–2.303), consistent with its role in hydrolyzing cellulose and hemicellulose in paper mill sludge via extracellular enzymes such as cellulases and xylanases (Normand *et al.* 2017; Morel *et al.* 2018). In CSTR 2, the microbial shift toward *Bacillus megaterium* (2.232 score) and *Bacillus firmus* (2.012 score) indicated acetogenic activity, where these species typically oxidize fatty acids to acetate and hydrogen (Hsueh *et al.* 2014; Mörtelmaier *et al.* 2019). *Methanogenic archaea*, critical for biogas production, were not identified due to MALDI-TOF MS's bacterial profiling bias (Vianna *et al.* 2021), highlighting a key methodological gap in resolving methanogen activity.

Temperature profoundly influenced microbial functionality, with 35 °C incubation driving a 5.6-fold increase in bacterial populations (42.00 ± 2.2 × 10^5 CFU/mL vs. 6.35 ± 0.7 × 10^5 CFU/mL at 28 °C) in CSTR 1 (Table 6). This aligns with mesophilic optima for hydrolytic enzymes (Zakavi *et al.* 2022) and supports enhanced substrate degradation rates. Methanol supplementation at 35 °C enriched methylotrophs like *B. firmus*, correlating with a 1.8-fold rise in VSS-normalized bacterial density (9.72 × 10^8 vs. 1.47 × 10^8 cells/gVSS at 28 °C) (Khot *et al.* 2012). The temperature-dependent community restructuring mirrors findings in full-scale paper sludge digesters, where 35 °C optimizes hydrolytic-methanogenic synergies while mitigating VFA accumulation (Kim *et al.* 2015; Schulthess *et al.* 2016). However, the lack of methanogen quantification (e.g., *Methanosarcina* or *Methanobacterium*) prevented direct links between temperature and methane yield, underscoring the need for complementary methods such as mcrA gene quantification (Schulthess *et al.* 2016).

CONCLUSIONS

This study identified the 1:3 PS:SS ratio as optimal for anaerobic co-digestion of recycled paper sludge, achieving the highest methane yield (918.66 mL CH_4/g VS_fed) with a short lag phase (1.59 days), reflecting balanced nutrient availability. In the two-stage CSTR system, CSTR 1 removed up to 70% of TCOD with stable acidogenic conditions (pH 6.64–7.33), while CSTR 2 maintained methanogenic conditions (pH 6.91–7.58), reduced the VFA/alkalinity ratio below 1, and sustained biogas production, yielding 1.8 ± 0.48 mL/g TVS_removed-day.

Kinetic modeling using Modified Gompertz and Logistic models confirmed good fit, with the Gompertz model offering better accuracy ($R^2 > 0.986$). The two-stage CSTR system exhibited clear functional stratification, driven by shifts in *Bacillus* species composition. Dominance of *Bacillus cereus* in CSTR 1 suggests a key role in the initial hydrolysis of lignocellulosic substrates, while the diversified consortium in CSTR 2 facilitated enhanced acidogenesis and methanogenesis. These findings highlight the metabolic adaptability of *Bacillus* spp. as a critical factor in stage-specific optimization of AD.

To enhance methane content and system performance, further development could focus on strategies such as extended HRT, selective enrichment of methanogens, and integration with biogas upgrading technologies. Additionally, pilot-scale validation and life cycle assessment are recommended to assess upscaling feasibility, supporting industrial applications, and circular economy implementation.

FUNDING

This work was supported by Suranaree University of Technology, Thailand Science Research, and Innovation (TSRI), and National Science, Research and Innovation Fund (NSRF) (Code number 195598).

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 1 December 2024; accepted in revised form 14 July 2025. Available online 6 August 2025

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Influence of sludge ratios and biokinetics leading to optimal design conditions for anaerobic co-digestion of excess sludge from the pulp and paper mill industry

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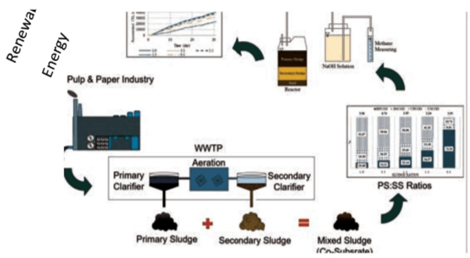
Abstract: This study investigates the optimization of co-digestion ratios of primary sludge (PS) and secondary sludge (SS) to enhance biogas production. The experiment evaluates various mixing ratios of PS and SS through biochemical methane potential (BMP) tests. Results indicate that the mixing ratio of 1:3 (PS:SS) exhibits the highest methane production potential at 997.19 ml CH_4/g VS_{fed}, with a lag phase duration of 1.59 days and a maximum methane production rate of 1,750 ml CH_4/d. Furthermore, statistical analysis reveals significant differences in average methane production potentials between mixing ratios, with the ratio of 3:1 showing notable disparities from ratios of 1:1 and 1:3. The study underscores the importance of optimizing co-digestion ratios for efficient biogas production and highlights the potential of the 1:3 ratio for practical implementation in biogas production systems.

Graphical Abstract:



Keywords: Anaerobic co-digestion; pulp and paper mill sludge; biogas production; biokinetics; COD fractions; circular economy

Introduction

The wastewater treatment system from the paper industry generates excess sludge in the range of 200-400 kg/ton-paper (Balwaik and Raut, 2011; Turner et al., 2022) and in the range of 40-50 kg-dry sludge/ton-paper (Mahmood et al., 2006; Jele et al., 2022). Generally, these sludges are consisting of 70% primary sludge (PS) and 30% secondary sludge (SS). The PS is generated from preliminary treatment processes such as dissolved air flotation (DAF) or primary sedimentation. Although a portion of PS can be repurposed for low-grade paper products like boards and crates, a significant amount still requires proper disposal. The SS is produced from secondary sedimentation tanks in the activated sludge

(AS) system. Preliminary data from a paper mill in Samut Sakhon Province, Thailand, indicate that there is a significant amount of excess sludge to be disposed of. This includes approximately 1,470 m^3/d or 25.87 ton-dry PS/d, and an average of 2,090 m^3/d or 36.83 ton-dry SS/d.

Previous studies on the properties of excess sludge generated by the paper industry. Both primary sludge (PS) and secondary sludge (SS) exhibit high moisture content, ranging from 53% to 77% (Simão et al., 2018). However, PS presents unique challenges due to its slow biodegradability. This is attributed to its composition, which includes approximately 5.7% lignin, 32-81% cellulose, and 6.5-12% hemicellulose (Simão et al., 2018; Lopes et al., 2018). PS also has a total solids (TS) content of 32-80%, with volatile solids (TVS) ranging from 32-58% of TS. Notably, a significant portion of the TVS (around 55%) is ash. Additionally, PS has a high chemical oxygen demand (COD) of approximately 64,300 mg/L (Lopes et al., 2018; Chakraborty et al., 2019). Despite containing organic matter, PS suffers from a low nutrient content. Its C/N ratio falls between 32:1 and 930:1, exceeding the optimal range of 20-30 for efficient anaerobic digestion (Veluchamy and Kalamdhad, 2017).

Several research suggest that anaerobic co-digestion (AnCoD) of PS and SS offers a promising solution for improved biogas production. Studies have demonstrated that a PS:SS ratio of 2:3 can generate significantly higher biogas yields (150-170 ml CH_4/g VS_{fed}) compared to pure PS substrate (Veluchamy and Kalamdhad, 2017; Bokhary et al., 2021; Lopes et al., 2018; Bayr and Rintala, 2012). AnCoD also outperforms pure SS as a substrate, with potential biogas production improvements of up to 59% (Bayr and Rintala, 2012; Sun et al., 2022). Based on these findings, this research aims to evaluate the impact of different sludge mixing ratios from the pulp and paper industry on the biodegradation ability and biochemical methane potential (BMP) through anaerobic co-digestion and biokinetic studies.

Material and Methods

Excess sludge sample collection and storage: This study utilizes excess sludge obtained from a paper mill located in Samut Sakhon province, Thailand, before the dewatering process. The samples comprise:

- *Primary Sludge (PS):* Collected from the primary sedimentation tank of the wastewater treatment system.
- *Secondary Sludge (SS):* Derived from the biological treatment tank (secondary sedimentation tank) of the activated sludge (AS) wastewater treatment system.

Following collection, the samples are stored at 4°C to maintain their integrity for subsequent analysis of physical and chemical characteristics. The collection is used to characterize biodegradation and BMP.

Experimental design: This research investigates the biodegradation ability and methane production potential of excess sludge from the paper industry through single digestion and co-digestion approaches. Batch assays under mesophilic conditions (@35±1.0°C) are employed to assess the impact of different mixing ratios on these processes. **Table 1** is shown the initial mixing and sludge characteristics.

- Initial pH: The initial pH of the digestion medium is maintained at 7.0 ± 0.01
- Mixing Ratios: The co-digestion experiments utilize PS and SS at various volumetric ratios (v/v): 1:0 (PS only), 3:1, 1:1, 1:3, and 0:1 (SS only)

Table 1 The initial mixing and sludge characteristics.

PS:SS ratios	Influent Substrate (mg/L)	
1:3	22,440	10,021

Biodegradation experiments:

The COD (Chemical Oxygen Demand) of the sludge was fractionated into four categories in Figure 2, following the method described by Wentzel et al. (1995). These categories are:

- Unbiodegradable Soluble COD (USCOD)
- Unbiodegradable Particulate COD (UPCOD)
- Readily Biodegradable COD (BSCOD)
- Slowly Biodegradable COD (BPCOD)

The total COD (TCOD) was measured, and the BOD (Biological Oxygen Demand) was determined after 20 days with inhibited nitrification using the OxiTop®-C measuring head (Boursier et al., 2005). The biodegradation fraction (BCOD) was then calculated from the TCOD and BOD20 values.

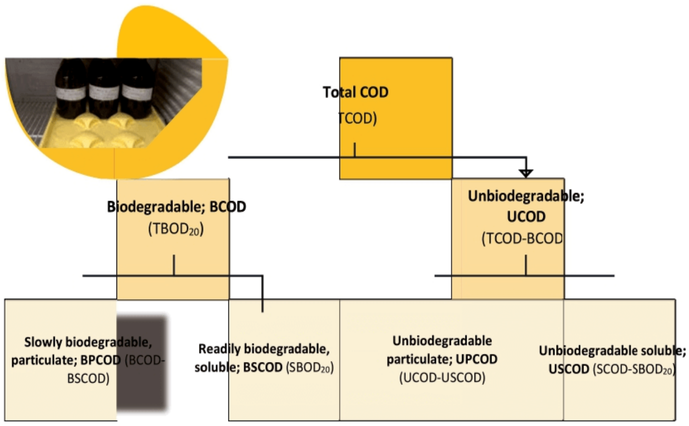


Figure 2 Biodegradation experimental set-up.

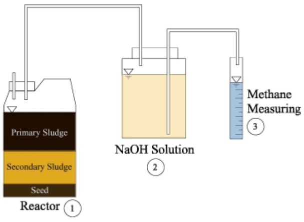


Figure 3 Installation of the BMP Test consists of 1) reaction tank, 2) container containing NaOH solution, and 3) graduated container for measuring the volume of NaOH solution replaced by methane gas.

Biochemical methane potential test (BMP Test) experiments: The reaction vessel was connected to a container filled with a 1.5 N sodium hydroxide (NaOH) solution for the absorption of CO2 and H2S. As methane gas was produced, it displaced the NaOH solution. The BMP Test installation is depicted in Figure 3. The temperature of all reaction vessels was maintained at 35±1.0 °C (mesophilic temperature). Prior to gas volume measurement, the reaction was shaken for 1 minute. The system operated with a Hydraulic Retention Time (HRT) of 31 days. All experimental sets were inoculated with 2 g VS/L (Rajput and Sheikh, 2019) of microbial inoculum, ensuring consistent inoculation across all sets. The pH was adjusted to 7±0.01 using HCl or NaOH prior to system initiation. NaHCO3 was utilized as a buffer, and anaerobic conditions were established by introducing N2 gas into the reaction for 3 minutes. Gas volume measurements were obtained by substituting the NaOH solution with a graduated syringe. Methane gas production was quantified daily through BMP test results. To minimize errors, each experimental set was conducted twice.

Biokinetics: The actual methane production in each experimental set can be assessed by subtracting the methane production from the blank experiment. The methane production potential will be calculated relative to the volatile solids (VS) concentration added per hydraulic retention time (HRT) in the BMP Test. The experimental results obtained can be used to generate a graph showing the relationship between the accumulated methane gas volume produced each day. This can be achieved using kinetic equations for the BMP Test, such as the modified Gompertz equation (Lay et al., 1996), as shown in Equation 1. SPSS software will be utilized for curve fitting and estimating kinetic parameters from the experimental data in the BMP Test. The efficiency of the model will be determined by the coefficient of determination, R-squared (R2).

$$M(t) = P \cdot \exp\{-\exp[(R\_m \cdot e)/P\ (\lambda - t) + 1]\} \quad (1)$$

Where M(t) is the accumulated methane gas volume produced (mL CH4), t is the cumulative time of methane gas production (d), P is the maximum potential methane production (mL CH4), Rm is the maximum methane gas production rate (mL CH4/d), **λ** is the lag phase duration (d), and e is the constant value (2.718).

Results and Discussion

Sludge Characteristics and COD Fractions

The physical and chemical characteristics testing of excess sludge generated from the wastewater treatment system of the pulp and paper industry, outlined in Table 2, reveals that both PS and SS exhibit remarkably high moisture content. This is attributed to the fact that the excess sludge collected represents the initial discharge from both the primary and the biological sedimentation tanks, which has not undergone the water separation process. This high moisture content is beneficial for the biogas digester. The total volatile solids (TVS) content of PS and SS ranges from 42 to 62% TS and 28 to 31% TS, respectively. There was evident that PS exhibits relatively high COD and VS values, indicating a substantial potential for biogas production, which can reach as high as 0.22 m³ CH4/kg-dry PS. Furthermore, it was observed that the organic content in PS is 2-3 times higher than that of SS. However, the biodegradation of only PS presents challenges due to the complex structure of fibers and cellulose, as well as excessive organic loading for the anaerobic digester. Numerous studies have highlighted that anaerobic co-digestion processes can effectively mitigate these challenges (Veluchamy and Kalamdhad, 2017; Bokhary et al., 2021; Lopes et al., 2018; Bayr and Rintala, 2012; Sun et al., 2022).

Table 2 Characterization of secondary sludge samples (Mean ± SD).

Characteristic	PS	SS
pH	6.02 ± 0.00	7.46 ± 0.03
Moisture (%)	95.41 ± 0.77	99.70 ± 0.01
Total COD (mg/L)	67,904 ± 1,575	10,653 ± 2,232
Soluble COD (mg/L)	10,774 ± 6,494	7,407 ± 1,166
Total Solids (mg/L)	24,390 ± 127	13,790 ± 1,626
Total Suspended Solids (mg/L)	19,550	11,340
Total Volatile Solids (mg/L)	15,010 ± 240	4,340 ± 665
Total Kjeldahl Nitrogen (mg NH_4-N/L)	37.35 ± 2.89	37.64 ± 1.65
Alkalinity (mg $CaCO_3$/L)	7,380 ± 355	752 ± 118
Volatile Fatty Acid (mg CH_3COOH/L)	2,341 ± 116	1,225 ± 53
C/N	1,840	274
$TBOD_{20}$/TCOD	0.35	0.83
$TBOD_5$/TCOD	0.23	0.40

Moreover, the nutrient content in PS sludge is relatively low, characterized by a significantly higher C/N ratio than the ideal range. Typically, the appropriate C/N ratio for anaerobic digestion systems falls within the range of 20 - 30 (Veluchamy and Kalamdhad, 2017). A high C/N ratio can result in rapid nitrogen depletion by methanogenic bacteria during protein synthesis, thereby limiting their ability to react further with the remaining carbon in the substrate. Consequently, this can lead to lower biogas production rates. In contrast, SS sludge exhibits high nutrient content, primarily nitrogen, resulting in a considerably lower C/N ratio compared to PS sludge. Additionally, both PS and SS demonstrate pH values ranging from 6.02 to 7.46, indicating a relatively neutral pH. Furthermore, their alkalinity, predominantly in the form of HCO3-, is relatively high. This elevated alkalinity aids in the better precipitation of positively charged ions in water, such as Ca2+, and can act as a buffer for acids generated during the acidogenesis process (Racho et al., 2012).

The assessment results of the COD fractions in the mixed sludge from the paper industry, with mixing ratios of 1:0 (only PS), 3:1, 1:1, 1:3, and 0:1 (only SS), reveal varying TBOD20/TCOD ratios of approximately 0.35, 0.40, 0.48, 0.58, and 0.83 respectively. These ratios indicate that in the mixing ratios of 1:0, 3:1, and 1:1, the organic matter present in the form of TCOD is predominantly difficult to biodegrade. Furthermore, the SBOD20/SCOD ratios are approximately 0.87, 0.97, 0.95, 0.95, and 0.70 respectively, suggesting that the organic matter in the form of soluble substances can be relatively easily biodegraded across all mixing ratios. Racho and Pongampornnara (2020) specifies that a BOD/COD ratio >0.45 indicates good biodegradability, 0.30-0.45 indicates relatively good biodegradability, 0.20-0.30 indicates some biodegradability, and if less than 0.20, the wastewater is not suitable for biological degradation. Based on these criteria, the findings suggest that the mixed sludge with ratios closer to 1:0 (only PS) and 3:1 exhibit relatively good biodegradability, while the ratios closer to 0:1 (only SS) may have limited biodegradability potential.

From **Figure 4**, it is evident that in the mixing ratios of 1:3 and 0:1, predominantly biodegradable COD fractions constitute 57.55% and 82.75% respectively of the total TCOD in the sludge, indicating a higher proportion of SS compared to PS. Further breakdown reveals that in the mixing ratios of 1:3 and 0:1, this biodegradable fraction is divided into BSCOD (Rapidly Biodegradable fraction), comprising 23.18% and 8.41% respectively of the total TCOD in the sludge, and BPCOD (Slowly Biodegradable fraction), comprising 34.37% and 74.34% respectively of the total TCOD in the sludge. Consequently, the proportion of COD that cannot be biodegraded is only 42.45% and 17.25% respectively of the total TCOD. These findings suggest that sludge with mixing ratios of 1:3 and 0:1 possesses high biodegradable fractions, as most of the organic matter comprises unbiodegradable fractions in lesser proportions, primarily found in PS. This makes it suitable for biogas production.

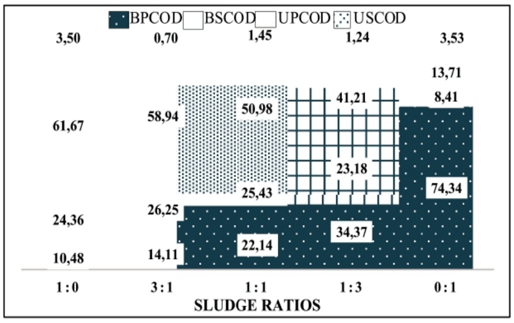


Figure 4 The COD fractions in various PS:SS mixing ratios.

Influencing of Sludge Mixing Ratio on Biogas Production

The investigation into evaluating the influence of different PS:SS ratios on BMP Test indicated that the maximum potential methane production was observed at varying proportions of 1:0, 3:1, 1:1, 1:3, and 0:1, with corresponding values of 23,684, 36,394, 38,510, 39,973, and 32,188 ml-CH4, respectively, as illustrated in **Figure 5a.** Of note is the proportion of 1:3, which demonstrated superior methane production potential compared to other co-digestion ratios and even outperformed the single-substrate digestion of PS and SS. The daily measurement of gas volume within the system enabled the computation of cumulative methane gas production for each blending ratio under investigation. Subsequently, these findings were subjected to analysis using the modified Gompertz equation (Lay et al., 1996) through the utilization of SPSS software, leading to the generation of predictive experimental outcomes, as illustrated in **Figure 5b.**

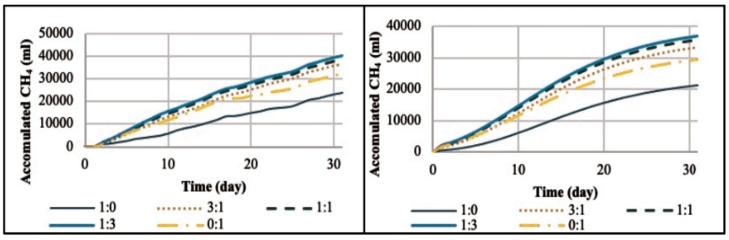


Figure 5 The Cumulative methane production resulting from the co-digestion of sludge at varying mixing ratios; (a) observed in the experiment and (b) obtained through fitting to Gompertz model utilizing the SPSS program.

When considering the methane production potential (CH4 Yield) from experiments with various mixing ratios, as shown in Table 3, it is evident that at the proportions of 1:0, 3:1, 1:1, 1:3, and 0:1, the methane production potentials are 353.72, 628.33, 747.59, 997.19, and 1,280.80 ml CH4/g VSfed, respectively. This study reveals that SS exhibits a higher methane production potential compared to other mixing ratios, consistent with the fact that SS has a higher proportion of particulate biodegradable COD than other mixtures. However, the mixing ratio of 1:3 demonstrates a higher production potential than other mixtures, including single-substrate digestion of PS, which, at a 1:3 ratio, still has a lower proportion of particulate biodegradable COD than single-substrate digestion of SS. Additionally, this finding aligns with the research conducted by Sun et al. (2022), which found that anaerobic digestion of SS alone yields higher methane production compared to PS. Moreover, in mixed PS and SS, it is found that at a mixing ratio of 1:3, there is a higher potential than ratios of 3:1 and 1:3. The results of the statistical testing for the differences in average methane production potentials in this paper indicate that the average CH4 Yield at the mixing ratio of 3:1 differs significantly from the mixing ratios of 1:1 and 1:3 at a confidence level of 95%.

Biokinetics

In the biokinetics analysis presented in **Table 3**, it is observed that the mixture ratio of 1:3, which yields the highest CH4 Yield at 997.19 ml CH4/g VSfed, exhibits a Lag phase duration of 1.59 days. This lag phase duration is attributed to the hydrolysis of substances that are not easily biodegradable. Moreover, this mixture ratio achieves the maximum methane production rate (Rm) of 1,750 ml CH4/d. These findings indicate that the mixture ratio of 1:3 is well-suited for implementation in a biogas production system. Conversely, the mixing ratios of 1:0, 3:1, 1:1, and 0:1 exhibit longer Lag phase durations. However, it is worth noting that the modified Gompertz equation effectively explains the variability of cumulative methane production (M(t)) at any given time with an accuracy exceeding 98.6% to 99% (as observed from R2). This high level of accuracy underscores the reliability of the model in predicting methane production kinetics across different mixing ratios.

Table 3 Kinetic value for Co-Digestion of Excess Sludge from the Pulp and Paper Mill Industry with diferent PS:SS ratio. (The resulting data obtained through fitting to Gompertz model utilizing the SPSS program.)

PS:SS ratio	CH_4 Yield ($ml\ CH_4/g\ VS_{fed}$)	P ($mL\ CH_4$)	R_m ($mL\ CH_4/d$)	λ (d)	R^2
1:0	353.72	23,684	1,030	4.21	0.986
3:1	628.33	36,394	1,614	2.29	0.989
1:1	747.59	38,510	1,703	1.73	0.99
1:3	997.19	39,973	1,750	1.59	0.989
0:1	1,280.80	32,188	1,366	1.46	0.987

Conclusions

In conclusion, this study demonstrates the effectiveness of co-digestion of primary sludge and waste acticated sludge for enhanced biogas production. The findings reveal that the 1:3 mixing ratio of PS and SS yields the highest methane production potential, surpassing single-substrate digestion and other co-digestion ratios. The optimized ratio exhibits a shorter lag phase duration and a higher maximum methane production rate, indicating its suitability for biogas production systems. Additionally, the modified Gompertz equation provides accurate predictions of methane production kinetics across different mixing ratios. These results emphasize the significance of optimizing co-digestion ratios to maximize biogas production efficiency and underscore the potential of paper sludge and sewage sludge co-digestion as a sustainable waste-to-energy solution in wastewater treatment facilities. Further research could focus on scaling up the optimized ratio for practical application and exploring additional factors influencing biogas production kinetics in mixed sludge digestion systems.

Acknowledgements

This work was supported by Suranaree University of Technology, Thailand Science Research and Innovation (TSRI), and National Science, Research and Innovation Fund (NSRF) (Code number 179348).

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